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RF exposure from short-range wireless communications: A study of Bluetooth and Wireless LAN

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ABSTRACT

The radio frequency electromagnetic exposure from a number of Bluetooth and wireless LAN devices was analyzed in this Master of Science thesis work. The interaction between the different devices and the user was studied by means of calculations and measurements of the Specific Absorption Rate, SAR and the electric and magnetic near fields. All results were compared with the appropriate exposure levels, basic restrictions and reference levels. The numerical algorithm used for the calculations was the Finite Difference Time Domain method, (FDTD) and the experiments involved measurements using E- and H-probes.

The FDTD calculations for 2450MHz, 1mW and 30mW, Bluetooth mobile devices showed that the maximum radio frequency exposure is far below the basic SAR restrictions. Also, a Bluetooth cordless phone base unit device transmitting 100mW is well in compliance with the basic restriction at a minimum realistic distance to a person (5cm). Simple models of wireless LAN antennas transmitting at 2.45GHz and 5.35GHz with output power levels 50mW and 200mW, respectively, gave results below the basic restrictions at 5cm distance between the devices and the user. Finally, an antenna transmitting 1W at 5.725GHz gave results below the basic restrictions at a distance of 7.5cm.

The agreement between the calculation and measurement results was very good in terms of shape, but about 10 – 60% differences were present for the absolute mass averaged SAR values.

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1 Introduction

1.1 Background

In the near future, many of the cables connecting electronic devices will be replaced by wireless communications. At home and at work a new technology called Bluetooth will be used to provide wireless connectivity between devices like laptop computers, printers, cameras, mobile phones and headsets. In offices, computers will be connected to each other using wireless local area networks (wireless LAN). These new technologies will use low-power radio transmitters, which enable short-range non line-of-sight communication.

People close to these transmitters will be exposed to parts of the emitted radio frequency energy. As for other wireless devices, the maximum exposure levels should not exceed established safety limits. The closeness of these devices to people, will be a cause of many questions and possible concerns about the radio frequency exposure. Studies of the exposure levels from Bluetooth and wireless LAN devices are therefore very important.

No such studies have been performed for Bluetooth up to now. Only one study related to wireless LAN and radio frequency has been published [1]. This study is not of direct relevance for this thesis work.

1.2 The purpose of this master thesis work

The purpose of this thesis was to use numerical calculations and experimental measurements to determine radio frequency exposure levels from Bluetooth and wireless LAN transmitters, and compare these with the safety levels in international standards and recommendations. The aim was to present information about the exposure, what levels can be expected and establish certain safety distances in the cases where it is needed. The report will elucidate the questions that may be raised about the exposure from these products.

The report begins with a short introduction to electromagnetic fields and the existing standards and recommendations concerning human exposure to radio frequency electromagnetic fields. The following chapter gives a brief overview of Bluetooth and wireless LAN. In that chapter information for example about frequency, output power and products is given. The chapter 'Exposure estimation' introduces the methods both for calculations and measurements and describes how these were performed. Finally the results and a discussion around the results are given before the summary and conclusions ends the report.

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2 RF electromagnetic fields

2.1 Fundamentals

The descriptive term *radio frequency (RF)* is used to describe electromagnetic waves with wavelengths ranging from app. 1mm to 30km. The wavelength is the length (m) between two nearby lying maximums on a wave. Frequency is the number of variations a wave makes per second. The product of the wavelength and the frequency is the velocity of the wave propagation. The corresponding frequency range is 10kHz to 300GHz. In table 2.1 examples of typical services are shown. Electromagnetic waves with wavelengths ranging from 1cm to 1m are called microwaves. The infrared spectrum comprises electromagnetic waves with wavelengths in range 1 μ m up to 1mm. Beyond the infrared range are the visible optical spectrum, the ultraviolet spectrum and finally x-rays and gamma rays (ionizing radiation).

Table 2.1. Frequency band designation and examples of typical services in each frequency range.

Frequency range	Typical services (examples)
3-30kHz	Navigation, sonar
30-300kHz	Radio beacons, navigational aids
300-3000kHz	AM broadcasting, maritime radio
3-30MHz	Telephone, telegraph, international broadcasting, amateur radio
30-300MHz	Television, FM broadcast, air-traffic control
300-3000MHz	Mobile phone, television, microwave ovens, Bluetooth, wireless LAN
3-30GHz	Microwave links, airborne radar, satellite communication, wireless LAN
30-300GHz	Radar, experimental

Electromagnetic fields comprise both electric and magnetic fields, which are caused by electric charges. The *electric field strength (E)* is a vector quantity that describes the force of an electric charge. The unit for the electric field strength is V/m. The *magnetic field strength (H)* is equal to the magnetic flux density B (Tesla) divided by the permeability of the medium. B describes the force from a magnetic field on a moving electric charge and is also a vector. The unit for the magnetic field strength is A/m. The electric and magnetic fields are coupled, that is because a time-varying electric field always is accompanied by a magnetic field, and vice versa, which gives the expression electromagnetic field. The power per unit area normal to the direction of the propagation of the electromagnetic wave is called the *power density (S)*. For plane waves the power density is given by the product of the rms electric field strength and the rms magnetic field strength, see (1.1). The power density for plane waves can also be expressed using either the E-field or the H-field and the impedance of free space, 120π , see (1.2). The unit for power density is W/m².

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$$S = EH \quad (1.1)$$

$$S = \frac{E^2}{120\pi} \quad \text{or} \quad S = H^2 120\pi \quad (1.2)$$

In radio communications, antennas are used to transmit and receive RF electromagnetic fields. Close to the antenna a so-called *near field* is formed. In the near field region the electric and magnetic fields vary from point to point and do not have a plane wave character. The outer boundary for the near field is defined as $d_{nf} = 2D^2 / \lambda$, where D is the largest dimension on the antenna. Outside the boundary the *far field* begins. Here the electromagnetic fields are approximately plane wave in nature and the electric and magnetic field vectors are orthogonal. There is no outer boundary for the far field. The power density in the main direction of the transmitting antenna can in the far field be calculated using the equation,

$$S = \frac{PG}{4\pi r^2} \quad (1.3)$$

where P is in input power in watt, G the antenna gain relative an isotropic antenna and r the distance.

The transmitted power is usually given in watt (W) or dBm. The unit dBm is relative to 1mW, i.e. 1mW=0dBm.

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2.2 Human RF exposure

When a human is exposed to electromagnetic fields the body reflects and diffracts most of the energy. The rest of the energy is absorbed in the body. The main mechanism is rotation of polar molecules, like water for example, induced by the electromagnetic field. By “friction” the rotation energy turns into heat. This method, heating by using radio frequency is well known and used for instance in microwave ovens, which use the frequency 2.45GHz. This frequency is not a resonance frequency for water, which many people believe. Mobile phones and other wireless RF-devices transmit such a low power that they do not cause any heating in the exposed body. Only a small amount of the power, several thousand times lower than the power used in microwave ovens, is absorbed in the body and no or only very small ($< 0.1^{\circ}\text{C}$) temperature increases can be detected.

The rate at which the RF energy is absorbed in a body, per kilogram of tissue, is called the *specific absorption rate (SAR)*. The SAR value can be calculated using (1.4).

$$\text{SAR} = \frac{\sigma E^2}{\rho} \quad (1.4)$$

where σ is the electrical conductivity (S/m) and ρ the density (kg/m^3) of the body. The unit of SAR is W/kg.

Electrical conductivity is a macroscopic constitutive parameter specific for each material. The unit for conductivity is siemens per meter, (S/m). Together with another material parameter, the electrical permittivity (ϵ), which is the product of the relative permittivity, specific for each material, and the permittivity for free space ($\epsilon_0 \approx 1/36\pi \cdot 10^{-7}$) the complex permittivity of the material is fully described. The permittivity affects the electric field and can also be defined as the factor between the electric displacement D and the electric field strength. The SAR value is, as shown in (1.4), depending on the conductivity and the density but also on the relative permittivity of the material, since the electric field strength is depending on the permittivity. The SAR value is also depending on the antenna, the distance between the antenna and the exposed tissue, the transmitted power and the frequency, since the magnitude of electric field strength is depending on those parameters.

The distance through which the amplitude of the travelling plane wave decreases by a factor of e^{-1} or 0.368 is called the *penetration depth* (δ) of a conductor.

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} \quad (1.5)$$

The penetration depth, or skin depth, depends on the conductivity of the tissue and the frequency. Using (1.5) the penetration depth for human tissues is about 9mm at 2.4GHz (Bluetooth and wireless LAN) and 3mm at 5.8GHz (wireless LAN).

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2.3 Exposure recommendations and limits

There are a number of national and international recommendations and standards for radio frequency exposure. The main part of them are based on recommendations set by one of the following international organizations; WHO (World Health Organization), IRPA (International Radiation Protection Association), IEEE (The Institute of Electrical and Electronic Engineers) and ICNIRP (International Commission on Non-Ionizing Radiation Protection). The European Commission, for instance, has based their recommendations on ICNIRP's guidelines [2]. The recommendations comprise basic restrictions and reference levels. In the frequency range 100MHz – 10GHz, the basic restriction is given by SAR and the reference levels are given as electric field strength, magnetic field strength and power density.

Basic restrictions

The basic restrictions are set to protect people from established health effects. In the frequency range between 100MHz and 10GHz, the basic restrictions are specified as SAR (Specific Absorption Rate) values (W/kg). The SAR limits are divided in two parts, an averaged value over the whole body and a localized SAR value averaged over smaller volume of tissue. The localized SAR limits in the two most important guidelines, from ICNIRP and IEEE, are slightly different. ICNIRP's localized SAR for head and trunk is calculated over 10g of tissue and IEEE's localized SAR is calculated over 1g of tissue. Also the exposure time varies with the guideline, six and thirty minutes, respectively, for the ICNIRP and IEEE, table 2.2. If the exposure time is shorter, the SAR value can be higher as long as the average does not exceed the restriction.

The basic restrictions have been set with wide safety margins. The safety factor for the public is about 50 and about 10 for occupational exposure. By occupational exposure, all exposure to electromagnetic fields experienced by individuals in the course of performing their work is meant [2]. In other words special devices only used in special occupations, where the person who will use the device get educated how to use it. Devices used by the general public should not exceed the general public basic restriction.

Table 2.2. The SAR limits for general public exposure [3]-[5].

Guideline	Exposure Time [min]	Frequency Band [GHz]	Whole-body SAR, [W/kg]	Localized SAR, [W/kg]	
				head and trunk	hands and feet
ICNIRP	6	0.01 – 10	0.08	2 , over 10g	4, over 10g
IEEE	30	0.01 – 6	0.08	1.6 over 1g	4, over 10g

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Reference levels

Since SAR can be difficult to measure in many situations, for example when the distance between the source and the exposed body is large, reference levels have been defined. The reference levels are derived levels in order to determine whether the basic restriction is likely to be exceeded. In the frequency range 100 MHz to 10GHz the reference levels are given as electric field strength (E [V/m]), magnetic field strength (H [A/m]) and power density (S [W/m²]). Table 2.3 shows the reference levels from ICNIRP's guidelines [2]. The electric field, the magnetic field and the power density shall all be measured in air without the presence of any body, and the exposure time shall be 6 minutes. The reference levels ensure that the whole body SAR value is below the basic restrictions, if the body is in the far field. Since the reference levels only can be used in the far field the product of the limit for the electric field strength and the magnetic field strength is app. the same as the limit for the power density, ($61 \cdot 0.16 = 10$) compare with table 2.3.

Table 2.3. Reference levels for general public exposure in the frequency band 2 – 10GHz [2]-[4].

Guideline	Electric Field Strength (E) [V/m]	Magnetic Field Strength (H) [A/m]	Power density (S) [W/ m ²]
ICNIRP	61	0.16	10

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3 Short-range wireless communications

3.1 Bluetooth

3.1.1 Introduction

Bluetooth is an interface that allows wireless communication between different devices, for instance a PC and its mouse. Bluetooth uses the 2.45GHz Industrial Scientific Medical (ISM) band, which is an unlicensed band open for anyone and used for many different devices like microwave ovens, garage door openers and cordless phones. Bluetooth is a small microchip, 9×9mm, which can fit into almost any electrical device. Besides the Bluetooth chip an antenna is needed. The fields of application are endlessly many. So far it is only the imagination that has set the limits for new applications.

In the beginning of 1998 five companies formed a special interest group (SIG) initiated by Ericsson. The five promoters were formed with special care, two market leaders on mobile telephony, Ericsson and Nokia, two market leaders in laptop computing, IBM and Toshiba, and one market leader in core, Intel. In May the same year, the Bluetooth Consortium announced itself to the world. The purpose was to establish a *de facto* standard for the air interface. Ericsson, though, had been working on Bluetooth technology since 1994. Since May 1998 many companies have joined the consortium as adopters of the technology. The special interest group now has over 1150 members.

The name, Bluetooth, was first just the working name for the technology, but was later accepted as the real name when the consortium was formed. Bluetooth is the English translation for Blåtand. Harald Blåtand was the name of a Danish viking who lived in the early Middle Ages, c. 911-991. He was the first king to reign over entire Denmark and Skåne, in the south of Sweden. Harald Blåtand also conquered the south of Norway and Christianized both Denmark and Norway.

3.1.2 Technology

Bluetooth uses an adaptive scheme that finds unused space in the frequency spectrum used, namely the ISM¹ band. The spectrum is divided into several channels, 1MHz wide. Bluetooth uses frequency-hop / time-division-duplex (FH/TDD). During a connection, radio transceivers hop from one channel to another. Each channel is divided into intervals (625 µs long) called slots and each slot has its own hop frequency. One packet of data covers one, three or five slots.

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Several devices are able to share the same channel. When two devices or more are sharing the same channel a pico net is formed. A pico net can for instance be constituted by a PC with accessories, see figure 3.1a. Each pico net has its own encryption to ensure privacy. A pico net can include up to eight different devices. Since there in the future might be more than eight devices needing to be able to communicate, the pico nets can overlap each other. Several pico nets form a scatter net, see figure 3.1b. One device can be part in several pico nets at the same time, but only be active in one at the time. The throughput of the system varies with a number of active users. Five users sharing the same 1MHz hop channel will make the throughput per user 200kbit/s and the aggregate throughput will be 20Mbit/s [6].

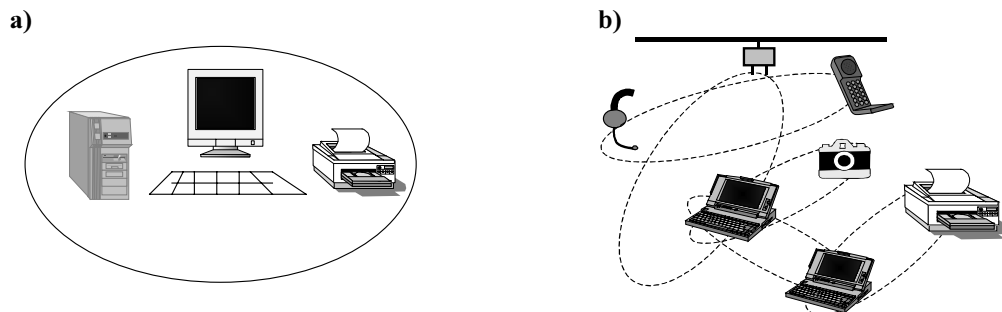


Figure 3.1. a) Pico net, consisting of a PC, mouse, keyboard, screen and printer. b) Scatter net containing several pico nets.

Frequency band

The frequency band used for Bluetooth is the unlicensed Industrial Scientific Medical (ISM) band. The same band is used by microwave ovens, garage door openers, cordless phones etc. The ISM band covers the frequencies 2.400 – 2.4835GHz in most of Europe and USA. The limits for the ISM band varies in different countries, see table 3.1.

Table 3.1. The Bluetooth frequency band for different countries [7].

Geography	Regulatory Range [GHz]
Europe (except France and Spain)	2.400 – 2.4835
USA	2.400 – 2.4835
France	2.4465 – 2.4835
Spain	2.445 – 2.475
Japan	2.471 – 2.497

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Power levels and power control

Bluetooth has three different power classes: 1mW, 2.5mW and 100mW. The first products on the market belong to the lower power class, 1mW (0dBm). The higher power level, 100mW (20dBm) will be more frequently used in the future. The lower power class has an optional power control, but power control is required in the higher class, see table 3.2. An equipment with a maximum transmit power of 100mW must be able to control its power down to 4dBm (app. 2.5mW).

Table 3.2. The three power classes defined for Bluetooth with the limits for the output power and in what areas power control is required [7].

Power Class	Maximum Output Power	Nominal Output Power	Minimum Output Power ¹	Power Control
1	100mW (20dBm)	N/A	1mW (0dBm)	4 to +20dBm, Required -30 ² to 0dBm, Optional
2	2.5mW (4dBm)	1mW (0dBm)	0.25mW (-6dBm)	-30 ² to 0dBm, Optional
3	1mW (0dBm)	N/A	N/A	-30 ² to 0dBm, Optional

Note 1. Minimum output power at maximum power setting.

Note 2. The lower range limit of -30dBm is not mandatory and may be chosen according to application needs.

Antennas

There are many different kinds of antennas proposed for the Bluetooth products in the future. No specific antenna has been made to suit all Bluetooth products and almost any kind of antenna is possible to use. Half wave and quarter wave dipole or monopole antennas with ground planes are always a possibility, mainly because they are cheap and easy to manufacture. Another common type of antenna is the so-called inverted F-antenna. A schematic drawing of an inverted F-antenna is shown in figure 3.2. Other antennas that may be used are patch antennas and printed circuit board antennas.



Figure 3.2. Schematic drawing of an inverted F-antenna that may be used in Bluetooth products.

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3.1.3 Applications and products

The first Bluetooth products will be on the market in the year 2000. A headset and a plug to add to a mobile phone (figure 3.3), both containing a Bluetooth chip and an antenna, are the products that will be available first from Ericsson. With those two products a cable between the mobile phone and the headset will not be necessary. There are many possibilities for using Bluetooth in future products, one of the main scenarios is the wireless office. The PC, screen, mouse and keyboard will all be equipped with Bluetooth chips that are able to communicate with one another and making the cables unnecessary. Another example of possible future applications is a Bluetooth chip and antenna integrated in a laptop, notebook and mobile phone. Then those devices will be able to communicate, for instance an address book can be kept up to date in all devices, even if a new address only is added to one of the devices. A third example is the three-in-one phone, a phone that works in the office with no charge, at home as a cordless phone with fixed-line charge and as a mobile phone everywhere else. For these applications the Bluetooth antenna usually will transmit at 1mW.

Bluetooth will also be used as an access point² with several phones and /or laptops connected to a network. Another application is cordless telephony, working similarity to the existing DECT³ systems. These applications will use the higher power level, 100mW at a maximum. One Bluetooth based cordless phone Ericsson is developing is expected to use a maximum output power of approximately 30mW.



Figure 3.3. Ericsson's first Bluetooth products; a plug containing Bluetooth connected to Ericsson's T28 mobile phone and a headset containing Bluetooth.

² An access point is like a small base station, connected to the wired system and able to supply a certain amount of devices, like mobile phones and laptops, with information. For instance the access point make it possible to connect to Internet from your laptop.

³ DECT is short for Digital Enhanced Cordless Telecommunications and is an international standard for cordless phones.

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3.2 Wireless LAN

3.2.1 Introduction

Wireless LAN⁴ is a network where the last piece of cable connecting to the user's terminal is replaced by radio communication. An access point transmits RF from the ordinary, wired network to the different workstations. The access point covers several devices, and a wireless local area network is formed. The area covered by one access point is called a cell, see figure 3.4. The products already on the market uses the unlicensed 2.4GHz Industrial Scientific Medical (ISM) band but future products will use a newly dedicated frequency band around 5GHz. In this new band the wireless LAN products do not have to share the spectrum with any other devices, which means that there will be less risk of interference during the transmissions. The new wireless LAN standard will help the development of a high-capacity, wireless data communication. The coverage range from one access point in the 5GHz frequency band is approximately 150m and each access point can give access to up to 50 different stations, like laptops or notebooks.

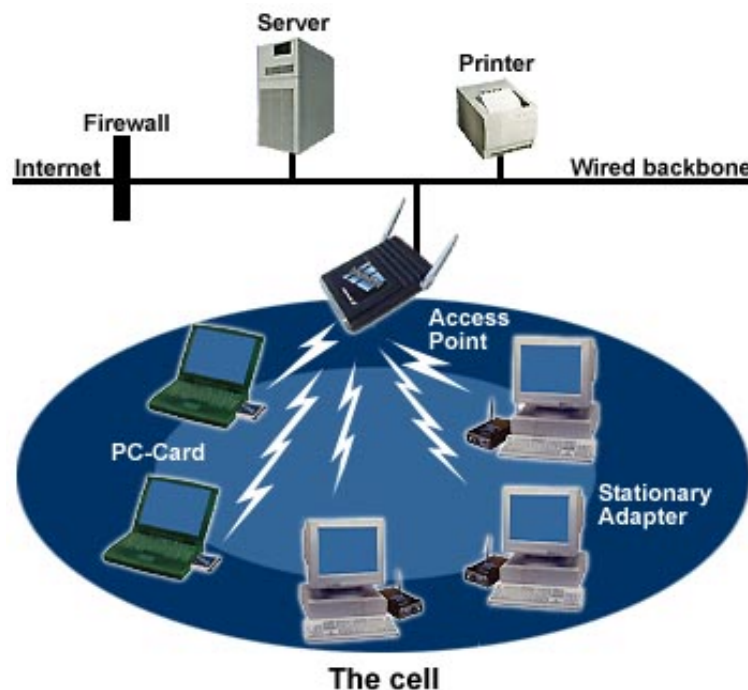


Figure 3.4. An access-point covers a circular area called a cell, which can contain several RF using devices.

⁴ LAN stands for Local Area Network, and is basically a network of cables connecting for instance PCs, like in an office building. LAN, as the name tells, only covers a small local area.

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3.2.2 Wireless LAN standards and technology

The currently most used standard for wireless networks is the IEEE 802.11 standard from 1997 [8]. The major advantage with this standard compared to previous standards is the interoperability between vendors. ETSI (European Telecommunications Standards Institute) is working on a new higher performance standard, the Hiperlan/2-standard, which is part of the Broadband Radio Access Networks (BRAN) project [9]. The new system will be operating in the current IP/Ethernet, but in the future it will be in the ATM⁵ environment. Hiperlan/2 will be using the new 5GHz frequency band [10].

The wireless LAN products now in use has a capacity of 3Mbit/s, but in the next generation wireless LAN products the capacity will be up to 20Mbit/s. The coverage varies with the product and whether the products are used indoors or outdoors. Indoors the coverage maximum can be up to 40 meters and the range outdoors is over 1000 meters when transmitting in the 5GHz frequency band.

Frequency and power

The current wireless LAN products use the 2.4GHz ISM frequency band. The next generation products will instead use a newly defined frequency band around 5.2GHz. The band is divided into at least two sections with different specifications of the maximum power level, (table 3.3). In Europe the lower frequency range, 5.15-5.35GHz will be used for indoor applications, while the higher range, 5.47-5.725GHz will be used both in- and outdoors. The maximum power levels in Europe are either 200mW or 1W, depending on the product. The access points are allowed a maximum output power up to 1W, while computer cards are allowed to transmit up to 200mW. In both power classes a power control is required. The bandwidth for the transmission from both a base station and a terminal is 20MHz [11].

Table 3.3. Frequency band and power levels in Europe and the US, with a maximum antenna gain of 6dBi [12].

Country	Placement	Frequency spectrum	Power level
Europe	Indoor	5.150 – 5.350GHz	200mW (23dBm)
	Outdoor + indoor	5.470 – 5.725GHz	1W, 200mW (30 resp. 23dBm)
US	Indoor	5.150 – 5.250GHz	10mW (10dBm)
	Outdoor + indoor	5.250 – 5.350GHz	50mW (17dBm)
	Outdoor + indoor	5.725 – 5.825GHz	200mW (23dBm)

Antennas

The antennas used in the Ericsson's current 2.4GHz products are half wave dipole antennas. Future products, using the 5GHz frequency band, will have different kind of antennas, probably mostly omni-directional.

⁵ ATM is short for Asynchronous Transfer Mode, which is a special environment well suited for wireless LAN.

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3.2.3 Applications and products

The wireless LAN systems allow, for instance, laptop users to have access to internet/intranet wherever they are in a specific area, like a building, an airport or a campus. In new offices it will not be necessary to connect every room with a cable, instead one or several access points can be attached to the walls and the rooms will be wirelessly connected. If an access point is placed well the whole office can be covered by it.

Ericsson has a small family of wireless LAN products on the market, all using the 2.4GHz ISM frequency band. Two of the products, an access point and a PC-card are shown in figure 3.5.

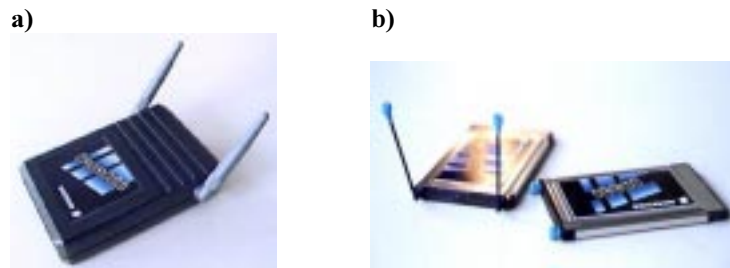


Figure 3.5. a) Ericsson's A3, wireless LAN access point. b) Ericsson's C3, wireless LAN PC-card.

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4 Exposure estimation

Both calculation and measurement have been used to estimate the exposure from Bluetooth and wireless LAN products in this thesis. Calculations were made on several products and scenarios while the measurements were made on a Bluetooth prototype and an existing wireless LAN product. The measurements were made both for the results themselves and for validation of the calculations. The methods for the calculations and the measurements have been used for several years at Ericsson Research in Stockholm to test mobile phones with good results. The main quantity to estimate was SAR, because of the closeness between most of the Bluetooth and wireless LAN products discussed and the user.

A simple calculation shows that Bluetooth products transmitting 1mW can not reach the localized SAR limits, figure 4.1. The strictest limit is 1.6W/kg calculated over 1g of tissue. This corresponds to an absorbed power of 1.6mW for 1g. Since 1mW is lower than 1.6mW, the basic restriction limits cannot be exceeded.

Limit: 2W/kg calculated over 10g of tissue \Rightarrow 20mW absorbed power in 10g

Limit: 1.6W/kg calculated over 1g of tissue \Rightarrow 1.6mW absorbed power in 1g

Figure 4.1. Calculation showing that the limits for SAR can never be exceeded for output power levels lower than 1.6mW, as is the case in the Bluetooth low power class, 1mW.

4.1 Methods for calculations and measurements

Two different methods have been used, one for the calculations and another for the measurements. The method used for the calculations is a numerical method called Finite Difference Time Domain method and for measurements the method used is the same as when testing mobile phones.

4.1.1 The calculation method – FDTD

The Finite Difference Time Domain Method, FDTD, is a numerical method well suited for computing SAR and electromagnetic fields. The computational space is divided into small cells or voxels. In these cells the different fields are computed in discrete points.

The FDTD method is based upon two of Maxwell's equations, the two curl equations.

$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} \quad (4.1)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (4.2)$$

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where **E** : the electric field strength [V/m]
D : the electric flux density [C/m²]
H : the magnetic field strength [A/m]
B : the magnetic flux density [T]
J : the current density [A/m²]

The relations between the flux densities and the field strengths, respective the current density are given in (4.3) – (4.5) below.

$$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} \quad (4.3)$$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} \quad (4.4)$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (4.5)$$

where ϵ_0, ϵ_r : the permittivity [F/m] and relative permittivity
 μ_0, μ_r : the permeability [H/m] and relative permeability
 σ : the conductivity [S/m]

The FDTD method is based upon the vector equations (4.1) and (4.2) in their differential form and a time and space partial derivative approximation. The two vector equations are discretized in a Cartesian coordinate system into six scalar equations by use of a special field configuration introduced by Yee [13]. In this approximation both the time and spatial derivatives are replaced by centered finite differences, (4.6).

$$\frac{\partial F}{\partial y} \approx \frac{F(x, y + \frac{1}{2}\Delta y, z, t) - F(x, y - \frac{1}{2}\Delta y, z, t)}{\Delta y} \quad (4.6)$$

where F is any function of x, y, z, and t.

The field configuration forms a so-called Yee cell, see figure 4.2. The electric components are shifted from the origin point (i,j,k) with half a grid step in each direction, respectively. The magnetic field components are placed in the middle of each plane that is normal to the field direction.

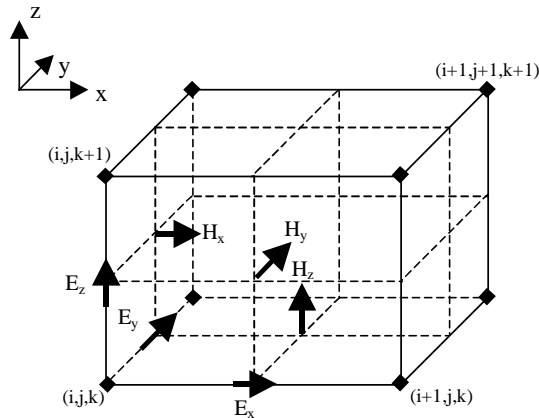


Figure 4.2. Field component location for the point with spatial indices (i,j,k) and with the Yee-cell notation.

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Using Yee's notation a function F of three Cartesian coordinates and time will be noted as (4.7).

$$F(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = F^n(i, j, k) \quad (4.7)$$

where i, j, k represents a certain calculation point and the side lengths in the so-called Yee-cell are represented by $\Delta x, \Delta y, \Delta z$. The discrete time step is denoted Δt .

One of the discretized equations, the electric field component in the x -direction, is shown in (4.8). This is a so-called leapfrog scheme, i.e. the electric field at time step $n+1$ depends on the magnetic field at time step $n+1/2$, which in turn depends on the electric field at time step n , and so on.

$$E_x^{n+1}(i + \frac{1}{2}, j, k) = E_x^n(i + \frac{1}{2}, j, k) - \sigma \frac{\Delta t}{\epsilon} \frac{E_x^{n+1}(i + \frac{1}{2}, j, k) + E_x^n(i + \frac{1}{2}, j, k)}{2} +$$

$$+ \frac{\Delta t}{\epsilon} \left[\frac{H_z^{n+\frac{1}{2}}(i + \frac{1}{2}, j + \frac{1}{2}, k) - H_z^{n+\frac{1}{2}}(i + \frac{1}{2}, j - \frac{1}{2}, k)}{\Delta y} - \frac{H_y^{n+\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}) - H_y^{n+\frac{1}{2}}(i + \frac{1}{2}, j, k - \frac{1}{2})}{\Delta z} \right] \quad (4.8)$$

Absorbing boundary conditions

The FDTD grid must be truncated by an absorbing boundary condition. There are two types of boundary conditions, those based on a plane wave approximation, such as Mur's first or second order boundary conditions, Liao's boundary condition, or boundary conditions imitating absorbing materials, like PML, Perfect Matched Layers. More information about boundary conditions is given by Kunz and Luebbers [14] and Taflove [15].

The software used in this thesis work used Liao's boundary condition, which is an absorbing boundary condition that uses a plane wave approximation of the electromagnetic wave locally at the boundary.

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The FDTD – software: XFDTD

The computer program used for the calculations was XFDTD, version 4.04. This program is developed by a US company called REMCOM INC. The program is available for UNIX and Windows platforms, costs app. \$12000 and has the capacity of computing $10000 \times 10000 \times 10000$ FDTD cells.

XFDTD has a graphical user's interface where the structure of the modeled object can be constantly present through out the modeling. To model more accurate it is also possible to zoom in the object. The program contains a number of predefined objects, such as boxes, plates, spheres and wires but it is also possible to edit every cell by hand. The result is displayed in two-dimensional color plots for any of the predefined and calculated planes. There are also a few features for post processing of the calculated results, such as localized SAR calculations and radiation pattern computing.

The computer

All calculations were carried out on a Sun Microsystems Ultra –30 with a 296MHz UIIs CPU and 768Mbyte RAM.

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4.1.2 The field probe measurement method

The method used for SAR measurements was the E-field probe technique, which is the only SAR evaluation method that provides sufficient accuracy. When using this method, a model of a human head, a phantom filled with tissue similar liquid is exposed to RF fields, and the electric field strength distribution is measured with a miniature probe. The SAR distribution can then be calculated from the electric field data. SAR test systems are commercially available and used for instance by mobile phone manufacturers and network operators. A number of standardization activities developing procedures for SAR measurements are being made by different standardization organizations, including IEEE.

The field strength measurements are made in free space without any phantom. The probes used are an electric field probe and a magnetic field probe.

The DASY3 System

The measurements were made in an anechoic chamber at Ericsson Research's *EMF Research Laboratory*, in Kista, Stockholm. The equipment used was a DASY3 system developed by Schmid & Partner Engineering AG, SPEAG, in Switzerland [17]. The DASY3 system consists of a robot, a controller and a computer, see figure 4.3. Different probes, depending on the type of measurement, are attached to the robot arm [18]. The measured magnitudes of the electromagnetic field are sent to the computer, which displays the results.

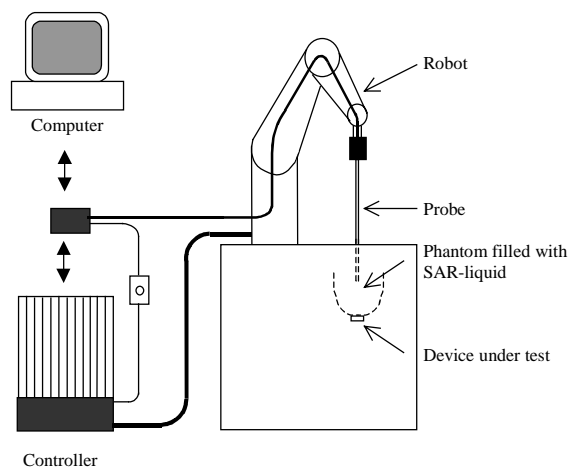


Figure 4.3. A schematic picture over the DASY3 system.

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In the measurements three different probes were used. When measuring the electric field in free space the isotropic E-field probe, SPEAG ER3DV4R, was used. It consists of three 3mm dipoles, each measuring the electric field in a specific orthogonal direction. This probe has a frequency range of 100MHz – 6GHz and a dynamic range of 2V/m – 1000V/m. The magnetic field was measured with a probe named SPEAG H3DV4R, consisting of three small metallic loops. The frequency and the dynamic range was 200MHz – 2.5GHz and 10mA/m – 2A/m, respectively. For SAR measurements a probe, SPEAG ET3DV6, was used. This probe measures the electric field strength in a SAR-liquid with a frequency range of 30MHz – 3GHz and the dynamical range is 5 μ W/g – 100mW/g. The isotropic error is the same for all three probes, +/-0.2dB.

For SAR measurements a phantom is filled with a special liquid. The SAR-liquid shall have the same value on the electrical parameters as the human tissue being modeled. The recipe for the SAR-liquid was a head tissue simulating liquid for 1900MHz taken from IEEE SCC-34 [19]. Some experiments were made trying to find a liquid with electrical parameters as close as possible to the ones used in the calculations. The best result was received with 45% glycol, Diethylene Glycol Butyl Ether, and 55% pure water. The entire result table is shown in Appendix, A2. The permittivity was 34.7 when measuring the headset and 38.5 for the access point. The electrical conductivity of the SAR-liquid was 2.0S/m. The temperature of the SAR-liquid was 19-20 degrees Celsius in all SAR measurements.

The phantom consists of each side of the human head and a flat section in-between, see figure 4.4. The flat section has been used in these measurements. The flat section has the dimensions 270 \times 280 \times 100 mm. The number of measured points can be defined arbitrary in the measurement in this system. A special measurement grid is made on the computer before every measurement.

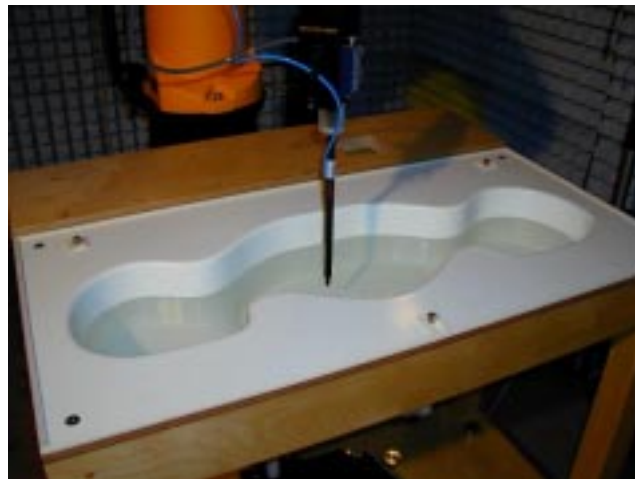


Figure 4.4. SAR-measurements made on the flat section of the phantom in the DASY3 system.

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4.2 Description of the calculations

The large amount of possible applications for Bluetooth and wireless LAN make the number of variations to calculate the exposure endlessly many. A number of calculations have been made for maximum but realistic exposure situations. The main thing to consider is which scenarios to take into account when calculating. That include type of product, which parts of the human body that will be most exposed and also the distance between the user and the transmitting antenna.

4.2.1 Exposure scenarios and device parameters

The calculations in this thesis were made on a rectangular lossy box. The box was chosen so that it could represent any part of the human body. The size of the box was $270 \times 270 \times 100$ mm, almost the same size as the flat section of the phantom used. In case of head exposure, the calculation results are higher than for a normal head, since the rectangular box is bigger than a normal head.

The distance between the user and the antenna varies with the product. Consider, for example, Bluetooth integrated in a mobile phone. It is possible to use the mobile phone near a head, in a pocket or a bag. The body is more exposed the closer the antenna is the human body. Therefore the case when the mobile is in the bag is not taken into account in this thesis. Another example is the head set, which of course is active very close to the head. Then there are all the other products, when the antenna, either Bluetooth or wireless LAN, is attached to a computer or a mouse. The user will be approximately twenty centimeters away from the antenna attached to the screen, but the user's hand will be close the antenna in the mouse.

Bluetooth

To cover all these scenarios two different distances were chosen to take into account. For the low power, 1mW, Bluetooth products that are used close to the body the distance was set to zero. The list below gives the scenarios in this field. In all cases the device and the antenna were covered with 2 or 4mm plastic. Read more about the modeling under 'Models in XFDTD'.

- The box to add to a mobile phone with an integrated F-antenna
- The head set, with an integrated F-antenna
- Bluetooth integrated in a mobile phone. An inverted F-antenna placed at the bottom near the microphone or in the middle of the mobile phone

Bluetooth products used with the higher power level were divided into two classes. The first class is when the Bluetooth chip and antenna is integrated in an access point transmitting 100mW. The distance was then chosen to 5cm, which is the normal distance used when calculating products not used close to the user. This distance corresponds to a minimum realistic exposure distance. At all longer distances the exposure will be less. Calculations for two different ways to place the antenna were made. In the first case the monopole antenna pointed towards the rectangular lossy box and in the other the antenna went parallel to the lossy box. The antenna was not covered by plastic in these calculations.

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The second class, cordless phones containing Bluetooth, was in these calculations chosen as a normal mobile phone with an either quarter wave or half wave monopole antenna, both with a ground plane and placed as a normal mobile phone antenna. There was a 2mm thick plastic cover around the mobile phone including the antenna. The output power level was 30mW and the distance was set to zero between the mobile phone and the rectangular lossy box.

Wireless LAN

The calculations on the wireless LAN have been divided into two sections. The first section comprises calculations and measurements on the products already existing on the market, using the 2.4GHz band. The distance between the device and the lossy block was set to 5cm and the antenna was covered with 2mm plastic.

The second section is dealing with the products and technology still to come, using the 5GHz frequency band. Two different frequencies have been used for these calculations. The first one, 5.725GHz was selected because it is the highest frequency in the span, 5.47-5.725GHz, the future access points are planned to use. That frequency caused the highest exposure. The second frequency, 5.35GHz, is the highest for the other products, like PC-cards, which use the span 5.15-5.35GHz. In both frequency bands the distance was set to 5cm and the antennas was not covered by any plastic. In the higher 5.7GHz frequency band the maximum output power was 1W, while the maximum output power in the 5.3GHz band was 200mW.

Tissue types

Three tissues, 'brain', 'muscle' and 'skin', were chosen to be used in the Bluetooth calculations. 'Brain' was chosen because several devices, like the headset is used close to the head. The 'muscle'-calculations cover the cases when the mobile phone is kept near the body, like in the breast or trousers pocket. Finally, 'skin' which is the tissue always closest to the source and often the tissue absorbing most at these frequencies. The same tissues have been calculated for wireless LAN transmitting with a frequency of 2.45GHz.

When calculating wireless LAN in the higher frequency band, 5GHz, two tissues were used, 'skin' and 'muscle'. The reason for this choice was that the penetration depth in this frequency band is so small that almost all power is absorbed the skin. Muscle is the most common tissue in the body and is here chosen to represent almost any part of the body. Brain tissue is not likely to be exposed since skin and skull cover the brain tissue and the power will be absorbed in those two layers.

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Physical parameters for the tissue types

The three different tissues, brain, muscle and skin all have different dielectrical properties. There are three physical parameters to consider in these calculations: conductivity, permittivity and density. The values used for the three materials at frequency 2.45, 5.35 and 5.725GHz are shown in table 4.2.

Table 4.2. Conductivity, permittivity and density for different tissues for 2.45, 5.35 and 5.725GHz, performed by Gabriel [16].

Tissue	Frequency [GHz]	Relative Permittivity (ϵ)	Conductivity (σ) [S/m]	Density (app.) [kg/m ³]
Brain (averaged)	2.45	42.5	1.5	1030
Muscle (averaged)	2.45	54.4	1.8	1040
	5.35	49.6	4.7	1040
	5.725	49.1	5.1	1040
Skin (wet)	2.45	42.9	1.5	983
	5.35	39.2	3.9	983
	5.725	38.7	4.2	983

The brain contains of mainly gray and white matter, therefore an averaged value of the brain parameters has been used. The parallel and the transverse fibers in the muscle have slightly different permittivity and conductivity values, therefore an averaged of those have been calculated. Finally, wet skin has higher permittivity and conductivity than dry skin. Taking the worst case means that wet skin was the tissue used.

4.2.2 Modeling in XFDTD and calculation properties

Choice of grid step

First of all the Nyqvist criteria has to be fulfilled but according to Kunz & Luebbers [14], the grid step when using FDTD shall be at least one tenth of the wavelength. The wavelength in a tissue is shorter than the wavelength in free space. The relationship between the different wavelengths is shown in (4.7).

$$\lambda_{issue} = \frac{\lambda_{free space}}{\sqrt{\epsilon_r}} \quad (4.7)$$

The wavelengths in the different tissues and one tenth of the wavelengths are shown in table 4.3 and 4.4. The numbers shown in the two lowest rows are factors between the grid step size and one tenth of the wavelength. These factors should ideally be at the most 10.

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Table 4.3. Wavelengths in different tissues for 2.45GHz, the demand that the grid step shall be at least one tenth of a wavelength and different factors for the grid step sizes used.

	Brain	Muscle	Skin
Permittivity	42.5	53.6	42.9
λ_{tissue} [mm]	18.4	16.4	18.3
$\frac{\lambda_{\text{tissue}}}{\Delta x}$ $\Delta x=1\text{mm}$	18	16	18
$\frac{\lambda_{\text{tissue}}}{\Delta x}$ $\Delta x=2\text{mm}$	9.2	8.2	9.2
$\frac{\lambda_{\text{tissue}}}{\Delta x}$ $\Delta x=3\text{mm}$	6.1	5.5	6.1

From table 4.3 it can be seen that in the 2.4GHz band the grid step should be chosen to be less than 2mm, since the factors on the lowest row are all below ten, but still close. Due to the time reduce for the calculations when using the grid step 2mm instead of 1mm, the 2mm-grid step was used. The 3mm-grid step was only used when a 3mm human head model was used. Since it was of interest to calculate on the human head model, a minor test was made to see how the grid step affected the results. The test is described in Appendix, A1. The result showed that the ratio of the input power and the radiated power used in the calculation decreased with an increasing grid size. The maximum SAR value and the average SAR value calculated over 10g was approximately the same, but the average SAR value calculated over 1g increased with increasing grid size.

In table 4.4 it is shown that the grid step in the 5GHz frequency band should be chosen to somewhere between 0.5mm and 1mm to fulfill the demand that the grid step should be maximum one tenth of the wavelength. In these calculations the grid step was chosen to 1mm with one calculation with a 0.5mm-grid step as a reference calculation. The simulation time was very long, so the box was made smaller. The dimension of the smaller box was $150 \times 150 \times 20$ mm, which should not affect the results in a remarkable way.

Table 4.4. Wavelengths in different tissues in the 5GHz frequency band, the demand that the grid step shall be at least one tenth of a wavelength and the factor for the 1mm-grid step used.

	Muscle 5.725GHz	Skin 5.725GHz	Muscle 5.35GHz	Skin 5.35GHz
Permittivity	49.1	38.7	49.6	39.2
λ_{tissue} [mm]	7.45	8.39	7.94	8.93
$\frac{\lambda_{\text{tissue}}}{\Delta x}$ $\Delta x=1\text{mm}$	7.4	8.4	7.9	8.9
$\frac{\lambda_{\text{tissue}}}{\Delta x}$ $\Delta x=0.5\text{mm}$	14.9	16.8	15.8	17.8

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Models in XFDTD

The Bluetooth headset was modeled as three parts, the antenna, the microphone and the rest as a box. The three parts were put together, which gave the result shown in figure 4.5. The box, see figure 4.5b, had the outer dimensions (length×width×depth) 36×20×28 mm, the microphone 94×4×4 mm and the antenna had the dimensions 24×8×4 mm. There was a 2mm plastic layer on each side of the modeled headset. The microphone, just being 4 × 4mm had a metallic wire in the middle. The antenna comprised a metallic plane 4mm wide reaching down to a metallic plane inside the box. The ground plane was place 8mm from the bottom’s exterior side.

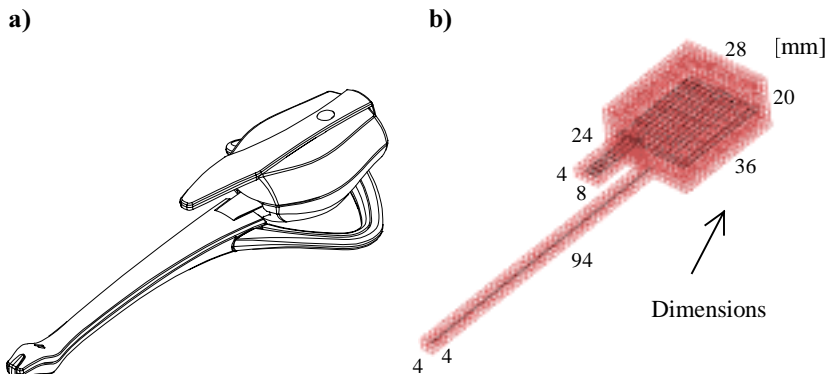


Figure 4.5. a) A drawing of the Bluetooth headset b) The same headset modeled in XFDTD with the outer dimensions given.

The Bluetooth mobile phone assessor was modeled as a rectangular box with the outer dimensions 46×20×10 mm and a ground plane placed 4mm from the side closest to the user. The plastic layer was 2mm. An inverted F-antenna, as in figure 3.2 was modeled, with the dimensions 4×18 mm, 2mm high. The placement of the antenna is shown in figure 4.6.

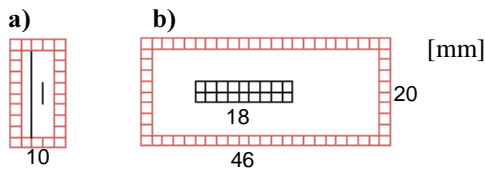


Figure 4.6. Schematic picture from XFDTD, showing the placement of the inverted F-antenna in a Bluetooth mobile phone plug. The grid step is 2mm. a) The cross-section shows the ground plane and the antenna. b) The cross-section shows the placement of the antenna.

The calculations made on mobile phones with a Bluetooth antenna included, was modeled similar to the Bluetooth box above. The mobile phone was made as a rectangular box, with 4mm plastic, and the outer dimensions 100×46×20 mm and the ground plane was placed 8mm from the size closest to the user. The size of the antenna is the same as in the box to add to a mobile phone and the placement of the antenna 52mm above the bottom, see figure 4.7.

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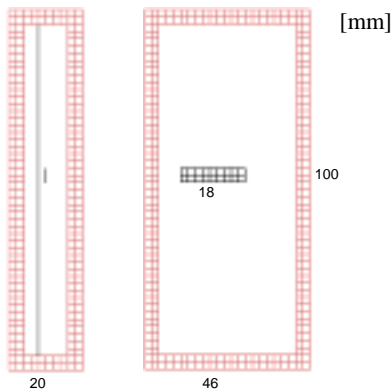


Figure 4.7. Model of a Bluetooth containing mobile phone with an inverted F-antenna situated below the keypad.

The model of the Bluetooth cordless phone was made very similar to the mobile phone with the integrated Bluetooth antenna. The outer dimensions were the same and a quarter wave monopole antenna (length 30mm covered with 2mm plastic) was placed as on a normal mobile phone. Calculations were also made when the transmitting antenna was a half wave dipole. For the base station the antenna was modeled in two ways. A 30mm monopole antenna was above a ground plane, 120 × 96mm. In the first case the antenna was placed at the middle of the ground plane pointing towards the rectangular box. From the edge of the antenna the distance to the rectangular box was 5cm. In the other case the antenna was parallel to the ground plane, pointing upwards. The distance between the rectangular box and the ground plane was 5cm.

Ericsson’s wireless LAN access point at 2.45GHz was modeled as a metallic box with two half wave dipole antennas. The antennas were metallic wires covered with 2mm plastic and 2mm air, see figure 4.8.

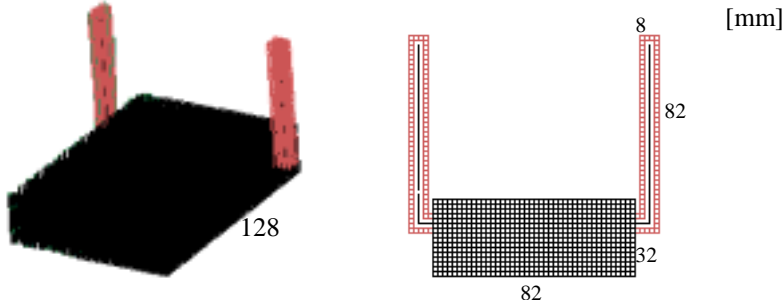


Figure 4.8. Model from XFDTD of Ericsson’s wireless LAN access point A3 (figure 4.4a) with the outer dimensions given.

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The wireless LAN products working in the 5GHz frequency band were modeled similar to the cordless phone base station antenna, i.e. a half wave (26mm) monopole antenna, without any plastic layer. The ground plane for the antenna transmitting 1W with a frequency of 5.725GHz was 30×30mm placed 52mm from the plane where the box is standing. The antenna was placed 7mm from the top and centered, see figure 4.9a.

The model for wireless LAN transmitting with the frequency 5.35GHz looks almost the same as the model for 5.7GHz, see figure 4.9b. The size of the ground plane is 40×80mm and the antenna is pointing straight upwards from the middle of the side of the ground plane. The ground plane was placed at the same level as the rectangular lossy box.

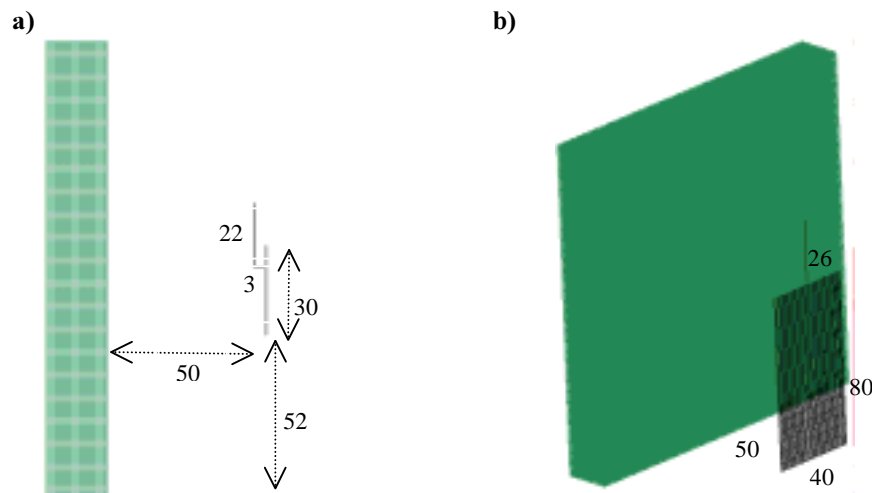


Figure 4.9. a) The model of a half wave monopole antenna for wireless LAN, frequency 5.725GHz.
b) Model of a half wave monopole antenna for wireless LAN transmitting with a frequency of 5.35GHz.

The calculations required processing times of 2-5 hours and memory between 57Mbyte and 200Mbyte. The total number of cells or voxels was in the range of $2.0 \cdot 10^6$ to $12.5 \cdot 10^6$. The time step was 3.85ps for the calculations with carrier frequency 2.45GHz and 1.93ps in the higher frequency range. The number of time steps varied between 1850 and 2200.

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4.3 Measurements

Complimentary measurements were made on two products, principally in order verify the FDTD calculated results. There was one Bluetooth prototype, the headset that soon will be on the market, and one access point for wireless LAN, already on the market. Three kinds of measurements were made. The first two were electric and magnetic field measurements in free space, and the third was a SAR measurement.

The setup for the field strength measurements of the headset is shown in figure 4.10a. For the SAR measurements the phantom was filled with SAR-liquid and the measured device was placed under the phantom. The position of the access point during the SAR measurement is shown in 4.10b.

Both the Bluetooth headset and the wireless LAN access point normally use a frequency-hopping mode, but during the measurements they were set to transmit continuously on one frequency. The Bluetooth headset transmitted an output power of 1mW and the frequency was 2.45GHz, while the wireless LAN access point transmitted a power of 50mW with 2.43GHz.

The grid in these measurements was chosen the same as for the XFDTD calculations. That would make it simpler to compare the results. The grid step, when measuring the fields for both the headset and the wireless LAN access point, was 4mm in-between the point in a plane above the transmitting antenna. The size of the planes measuring the headset were 60×92mm for the electric field and 60×100mm for the magnetic field. The field measurements for the access point were made in planes sized 84×132mm. For the SAR measurements the spacing between the measured points were 8mm in the plane and 4mm to the next plane. The size of the planes were 72×96mm measuring the headset and 88×136mm for the access point.

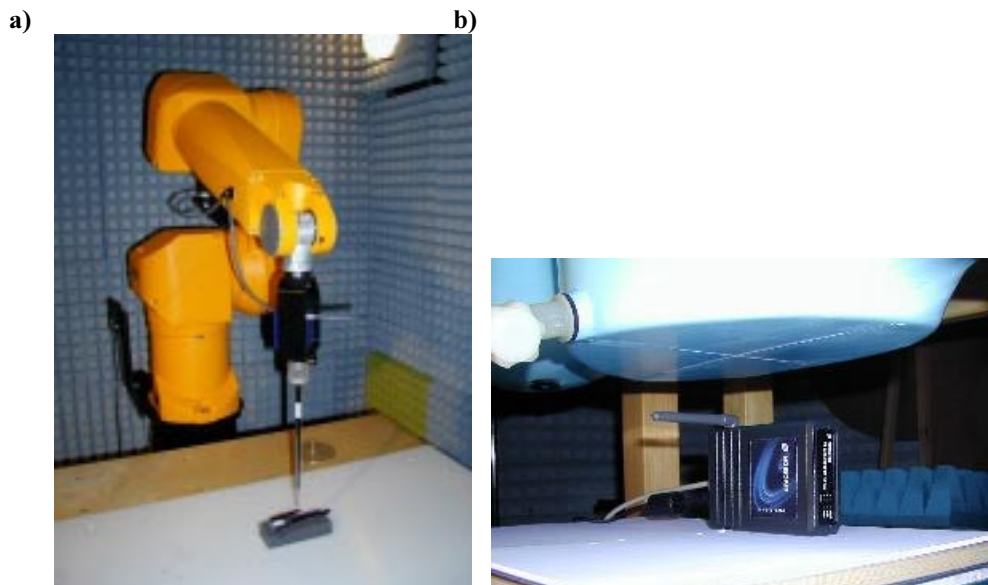


Figure 4.10. a) The DASY3 robot measuring the electric field from the Bluetooth headset. b) The access point placed under the SAR liquid filled phantom.

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5 Results and discussion

5.1 Calculation results

5.1.1 SAR distributions

Bluetooth

The 1mW Bluetooth products included in this thesis gave similar SAR results, both for the 1 and 10g averaged values. In figure 5.1 the averaged SAR values are shown for a mobile phone with a Bluetooth antenna, inverted F-antenna, placed at the bottom. As can be seen, the SAR values are well below the limits in figure 5.1a. In fact the SAR values are so small they can hardly be detected, in figure 5.1b the chart is enlarged one hundred times.

The SAR values, when using the head model, are slightly lower than the values calculated from the rectangular lossy box. The reason is that the area of the head is smaller than the area of the box and thus the coupling is smaller. The differences between the three chosen tissues are very small, as figure 5.1b shows. Highest values are given by the 'skin'. Therefore the 'skin' will be the tissue shown in all figures, since it shows the worst case and all tissues are supposed to be below the same limits.

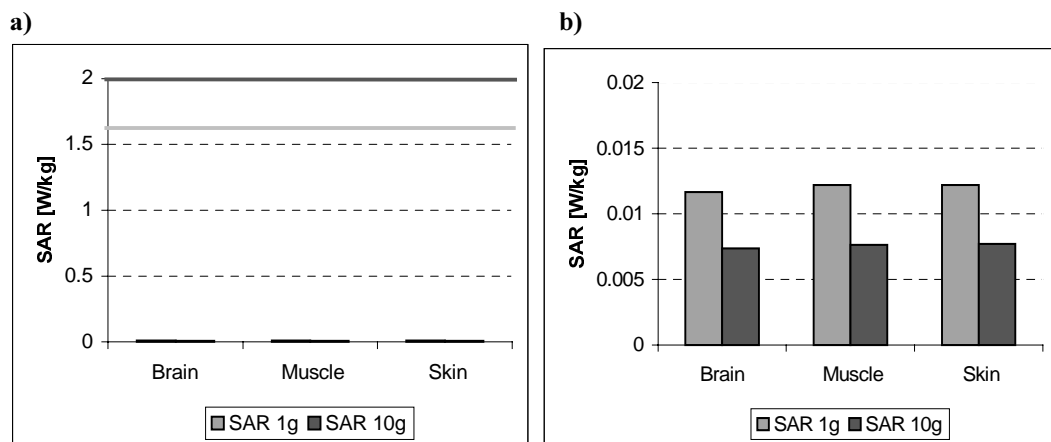


Figure 5.1. a) SAR-values, averaged over 1g and 10g of tissue, for a Bluetooth inverted F-antenna placed at the bottom in mobile phone. The antenna was transmitting 1mW with a frequency of 2.45GHz. The bars represent the three different tissues, brain, muscle and skin in a rectangular lossy box. The basic restrictions are marked with lines. b) Enlargement, 100 times, of figure 6.1a.

The plug to add at the bottom of a mobile phone gave slightly higher SAR values than the headset, but the values were still about 100 times below the basic restrictions. The main reason for the slightly higher SAR in this application was that the antenna in the model was placed 2mm closer to the plastic cover, which has strong effects on the amount of absorbed power.

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The SAR values were calculated in a plane situated 6mm from the outer edge of the calculated box closest to the headset. The Bluetooth headset was placed in two different positions. Either in its normal position with the antenna pointing outward from the user or backward, i.e. with the antenna pointing directly towards the rectangular lossy box, see figure 5.2.

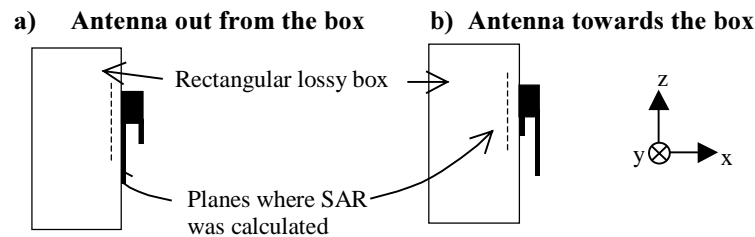


Figure 5.2. Schematic picture of the rectangular lossy box and the Bluetooth headset, placed in its two calculated positions. The picture also shows the plane 6mm from the edge where the SAR distribution was calculated (figure 5.3).

The SAR distributions given from XFDTD for the two different placements of the headset are shown in figure 5.3. The planes shown are contour plots of the distributions. A schematic drawing form of the headset is also added. The scale on the axis is the distance in centimeters from a reference point on the headset. As can be seen the result from the case when the antenna was pointing directly towards the box is higher than when the antenna is pointing outwards, but both maximum values are well below the average, over 1g and 10g, values that forms the basic restriction.

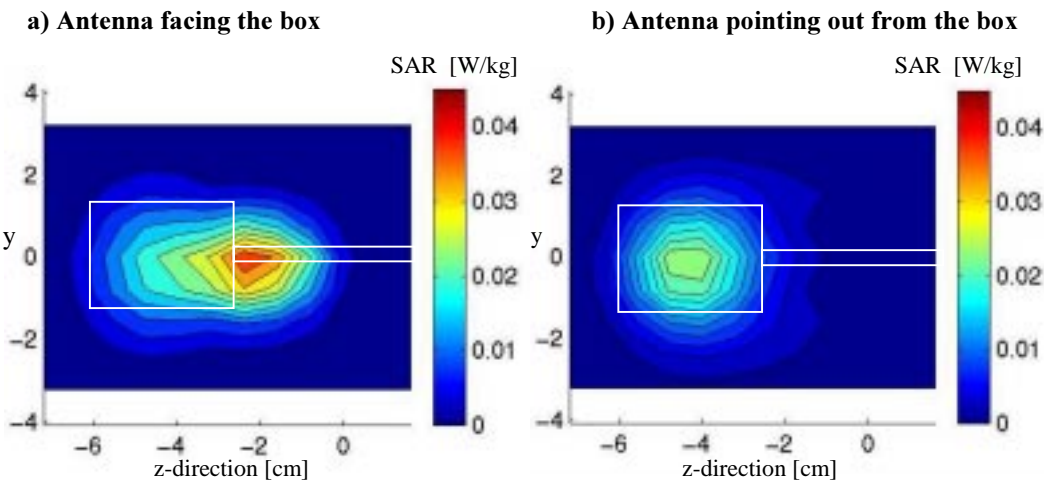


Figure 5.3. SAR distributions from the Bluetooth headset, where the antenna was transmitting 1mW with a frequency of 2.45GHz. a) The antenna in a backwards position, with the antenna pointing towards the box. b) The antenna in a normal position, i.e. the antenna is pointing out from the box.

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The higher power level, planned for Bluetooth products still to come, will give higher SAR values. The cordless phone, containing Bluetooth, able to communicate with the base station on the wall, transmits a power of 30mW. The average SAR values for a cordless phone with a quarter wave monopole antenna, over 1g and 10g respectively, are shown in figure 5.4. The calculations were made on all three tissues, but as described before ‘skin’ absorbed most of the power and is therefore shown in figure 5.4. As can be seen the values are well below the basic restrictions, marked with lines. The results from a calculation with a half wave dipole antenna gave very similar results. The differences were well inside the margin of error.

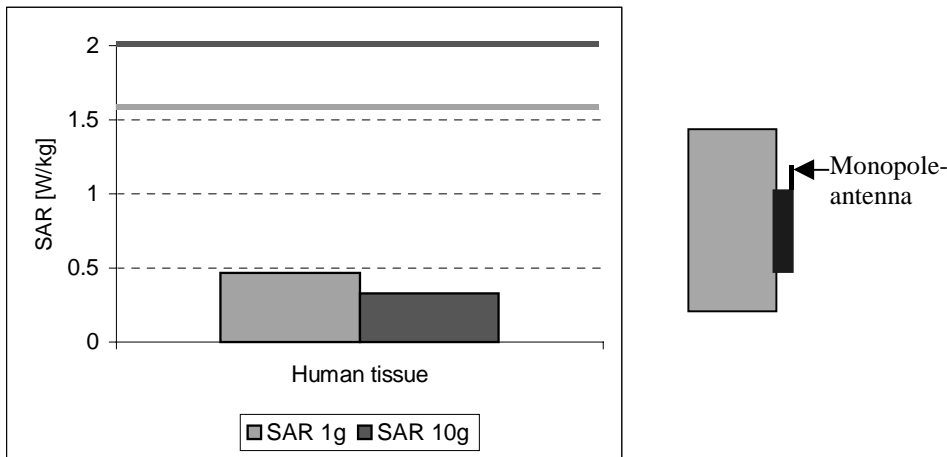


Figure 5.4. SAR- values for a Bluetooth cordless phone transmitting a power of 30mW with a quarter wave monopole antenna. The basic restrictions are marked with lines. The frequency was 2.45GHz and the mobile phone was placed as close as possible to the rectangular box.

The Bluetooth-containing access point, or the Bluetooth base station, has a maximum output power of 100mW. In the calculations a monopole antenna was pointing out from a ground plane. The antenna either pointed against the rectangular lossy box or went parallel to the box. The distance was set to 5cm. The calculations showed that the antenna placed parallel to the rectangular lossy box gave slightly higher SAR values. Skin was the tissue to absorb most power and in figure 5.5 the results from these calculations are shown. The SAR values are well below the basic restrictions marked with lines.

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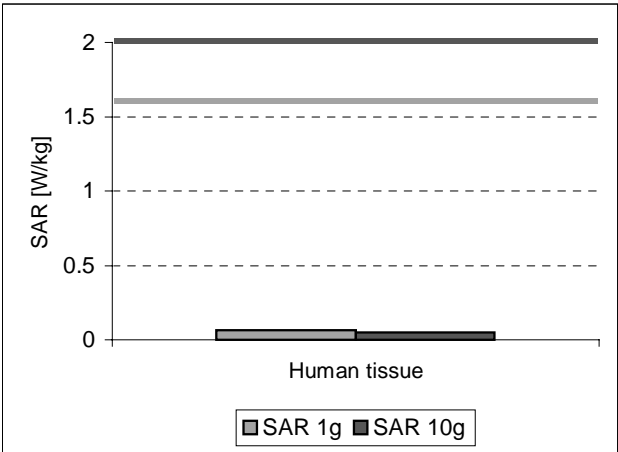


Figure 5.5. SAR values from a Bluetooth base station. The light shades represents the average SAR-value over 1g and the dark shades represents the average SAR-value over 10g. The basic restrictions are marked with lines in respective color. The distance is 5cm, the frequency 2.45GHz and the power transmitted was 100mW.

Wireless LAN

For wireless LAN transmitting with a frequency of 2.45GHz Ericsson’s access point A3 was the object to be calculated. The SAR values for this access point transmitting 50mW were well below the basic restriction limits, as shown in figure 5.6. The distance between the device and the tissue box was 5cm. All three tissues, brain, muscle and skin were measured and they all gave similar results. Skin had the highest average SAR values of the three tissues.

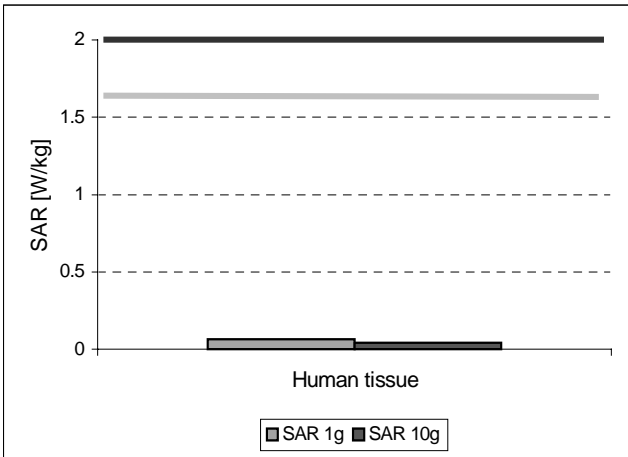


Figure 5.6. SAR-values calculated over 1g and 10g respectively for Ericsson’s wireless LAN access point A3. The frequency was 2.45GHz, the distance between the lossy block and the antenna was 5cm and the transmitted power was 50mW.

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A plane showing the distribution of the SAR values from the access point at the distance 6mm from the edge is shown in figure 5.7a. Notable is that the maximum SAR values cover a small area and the amount of absorption is then decreasing very quickly. The unit on the axis is centimeters, and the values are the distances from a special reference point.

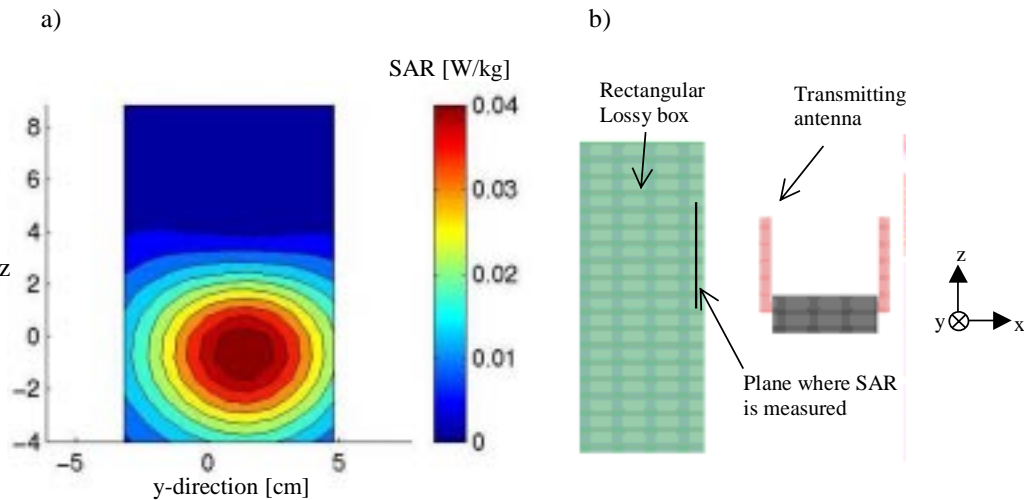


Figure 5.7. a) Contour plot of the SAR distribution from Ericsson’s wireless LAN access point A3 transmitting 50mW. The distance was 5cm and the frequency 2.45GHz. b) Model from XFDTD showing the placement of the access point, the antenna and the rectangular box.

For the calculations of SAR distributions in the higher frequency band very simple models were used. The wireless LAN PC-card, modeled as a small ground plane and a monopole antenna, had the SAR values shown in figure 5.8. The SAR values are a little higher in this calculation than in the previous ones, but still well below the basic restrictions. The distance between the antenna and the box was 5cm and the transmitted power was 200mW at a frequency of 5.35GHz.

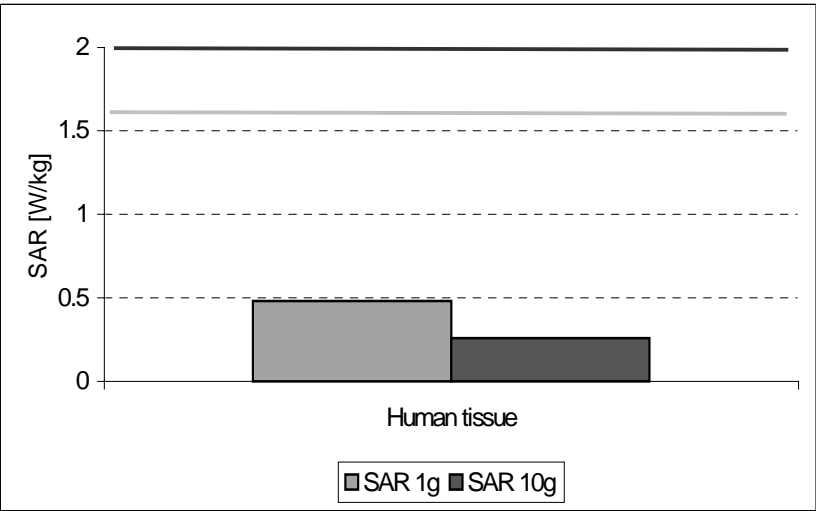


Figure 5.8. SAR-values for a wireless LAN PC-card transmitting 200mW with a frequency of 5.35GHz. The distance between the rectangular lossy box and the transmitting antenna was 5cm.

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In the higher frequency band, up to 5.7GHz, a dipole antenna with a ground plane was placed 5cm away from a rectangular lossy box. The results, in table 5.1, show that when transmitting 1W continuously for 6 minutes and the human tissue is placed 5cm away, the basic restrictions are exceeded.

Table 5.1. Averaged SAR values over 1g res. 10g for wireless LAN. The frequency was 5.725GHz. The distance between the dipole antenna and the box with tissue was 5cm and the transmitted power was 1W.

	Input power [W]	Max SAR 1g [W/kg]	Max SAR 10g [W/kg]
Basic restriction [W/kg]		1.6	2.0
Muscle	1	2.1	1.0
Skin	1	2.3	1.2

The conclusion from this is that either the distance has to be larger than 5cm or the power will have to be reduced. When the antenna was transmitting 1W and the distance was increased to 7.5 cm the SAR levels were not reached. Trying to find which output power that was needed to receive a result below the basic restrictions showed that the output power should be reduced to app. 700mW, see table 5.2.

Wireless LAN products (access points) using 1W output power will however be placed at such locations that the distances between the antenna and a person is much larger than 7.5cm. The real average power will also be less than 1W since the products will not be transmitting continuously.

Table 5.2. Averaged SAR values over 1g res. 10g for wireless LAN. The frequency was 5.725GHz. The distance between the dipole antenna and the box with tissue was 5cm and the transmitted power was scaled so that the 1g SAR values should be below the basic restriction.

	Input power [W]	Max SAR 1g [W/kg]	Max SAR 10g [W/kg]
Basic restriction [W/kg]		1.6	2.0
Muscle	0.75	1.5	0.7
Skin	0.65	1.6	0.8

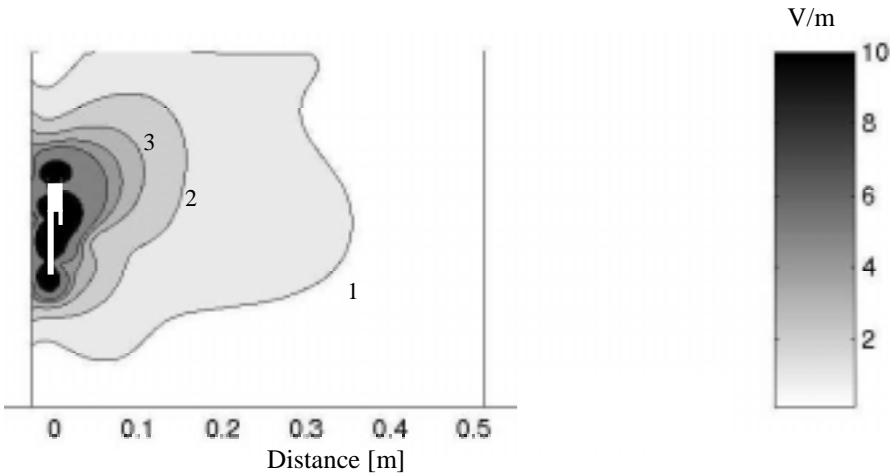
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5.1.2 Near field distributions

Bluetooth

Since the SAR values already have shown to be well under the basic restrictions, the calculations for the electric and the magnetic field are redundant. But still it can be interesting to see the magnitude of the fields and how fast they decrease. In figure 5.9 the distribution of the electric and magnetic fields for the Bluetooth headset is shown. The magnitudes are well below the reference levels. For the electric field, the magnitude at 50cm is approximately 1V/m, and for the magnetic field the magnitude is approximately 2mA/m.

a) Electric field



b) Magnetic field

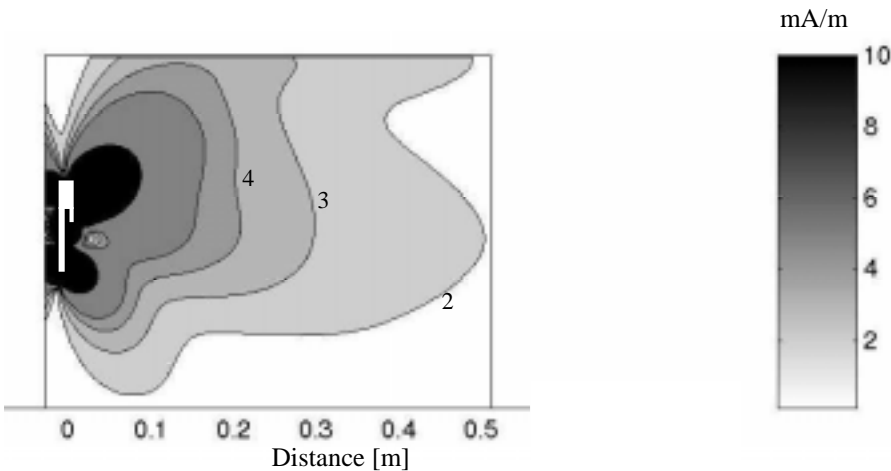


Figure 5.9. Fields from the Bluetooth headset shown as a cross-section 0 to 50cm from the transmitting antenna. a) Electric field where the contour lines represent 10, 5, 4, 3, 2 and 1V/m. b) Magnetic field where the contour lines shown are 10, 5, 4, 3, 2mA/m.

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To see the field distributions closer a plane orthogonal to the plane shown in figure 5.9 was calculated. The plane was place 6mm outside the antenna as shown in figure 5.10. The field distributions at this plane 6mm in front of the antenna show that the maximum values are very locally situated and that the fields decrease quickly, see figure 5.11.

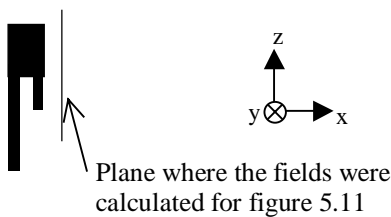


Figure 5.10. Schematic picture showing the plane in which the field strengths were calculated for the Bluetooth headset.

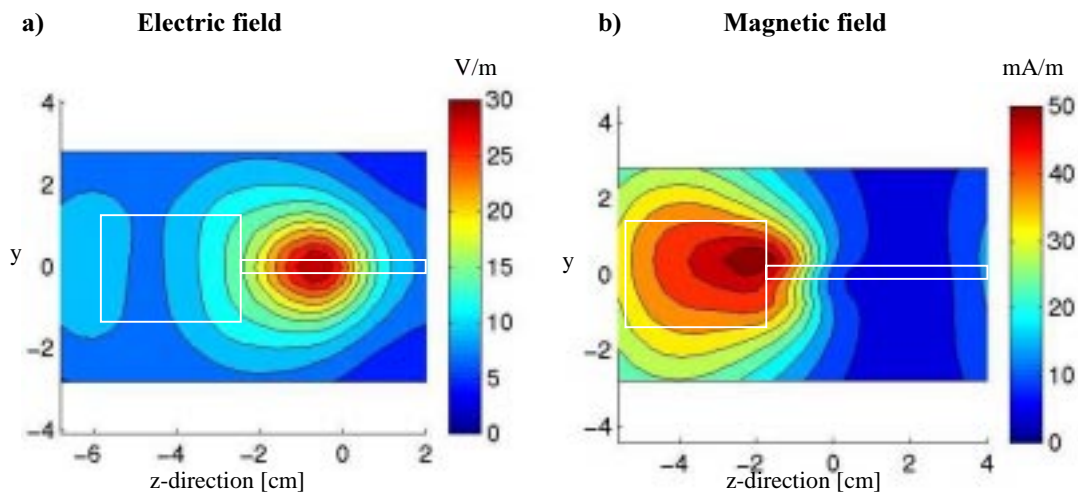


Figure 5.11. The field distributions, electric field (a) and magnetic field (b), given from the Bluetooth headset in a plane 6mm outside the headset as shown in figure 5.12. The frequency transmitted was 2.45GHz and the transmitted power was 1mW.

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When calculating the fields for Bluetooth's higher power class, 100mW, an ordinary dipole was chosen to represent the antenna. The field strength levels are reaching the reference levels approximately 3cm from the antenna, see figure 5.12. The output power is 100mW as for the Bluetooth cordless base station. For the cordless phones the transmitted peak power still is 100mW, but since the duty-cycle is one third the average power will be only 30mW. The field distribution can therefor be taken from figure 5.12 if the values are divided by the square root of three.

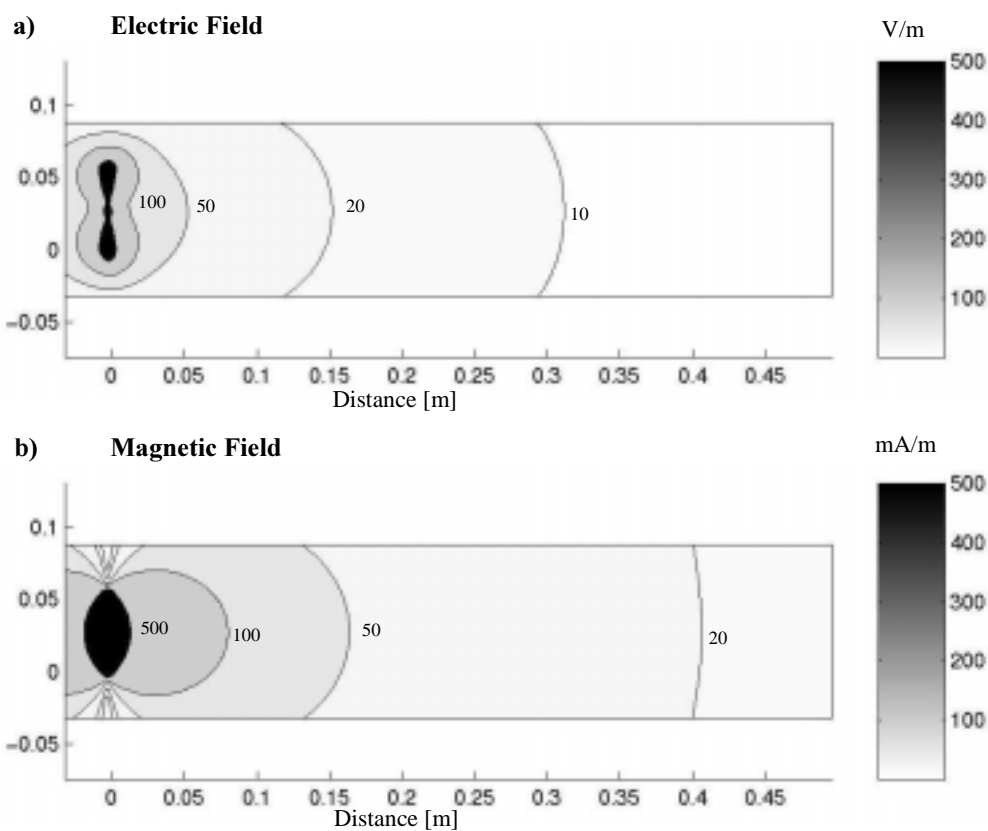


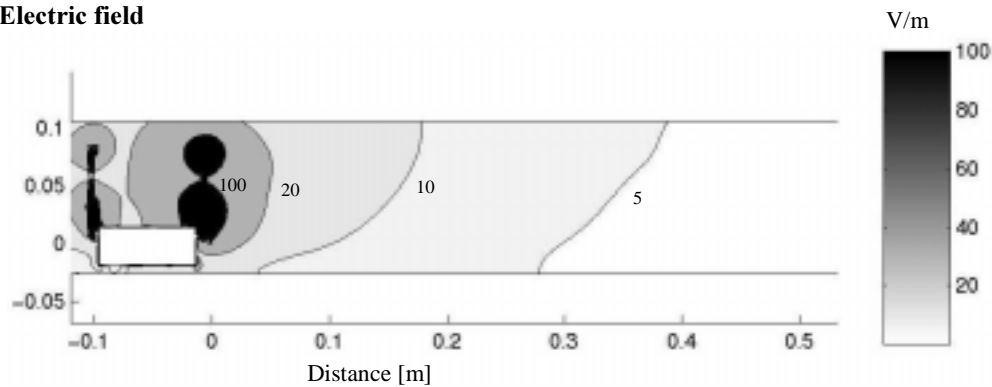
Figure 5.12. Electric (a) and magnetic (b) fields for a Bluetooth phone base station antenna - dipole from 0 to 50cm. The frequency was 2.45GHz and the transmitted power 100mW. The contours shown in figure a) are 500, 100, 50, 20 and 10V/m and in figure b) the contours are 500, 100, 50 and 20mA/m.

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Wireless LAN

Two calculations were made of the electric and magnetic fields from Ericsson's wireless LAN access point A3. The first calculation was made to see how fast the fields decrease. A plane showing a through-cut of the device, at distances up to 50cm is shown in figure 5.13. The other calculation was of the field distribution close to the device. A plane 5cm outside the transmitting antenna is shown in figure 5.14. The transmitted power was in both cases 50mW and the frequency was 2.45GHz.

a) Electric field



b) Magnetic field

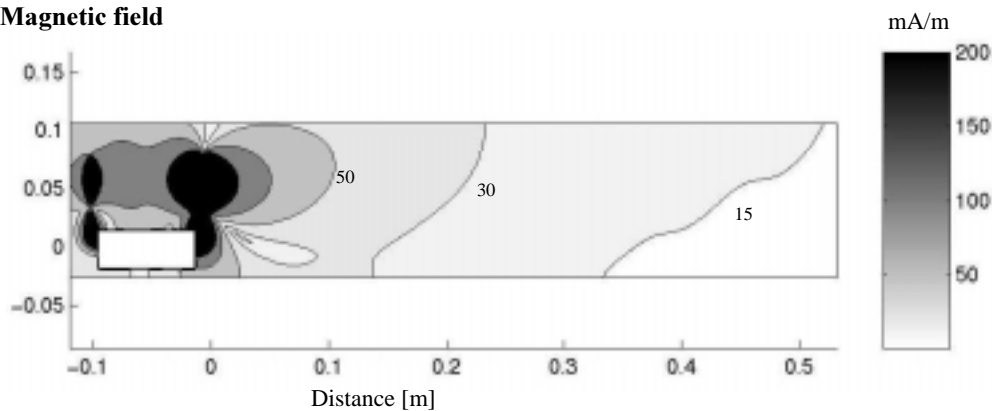


Figure 5.13. Electric (a) and magnetic (b) fields for Ericsson's wireless LAN 2.45GHz access-point A3 from 0 to 50cm. The power transmitted was 50mW and the frequency 2.43GHz. The contour lines shown for the electric field is 100, 20, 10 and 5V/m and for the magnetic fields the contour lines are 200, 100, 50, 30 and 15mA/m.

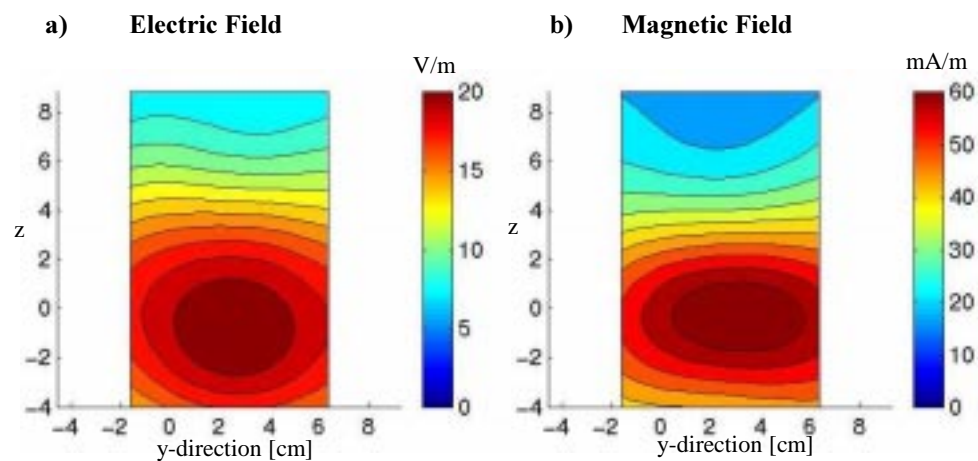


Figure 5.14. Contour plots over the electric (a) and the magnetic (b) field distribution from Ericsson’s wireless LAN access point A3 transmitting 50mW at frequency 2.45GHz. The distance between the calculated plane and the transmitting antenna was 5cm.

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5.2 Measurement results

5.2.1 SAR distributions

The SAR distributions were measured in the same plane as the calculated SAR distributions for the Bluetooth headset and Ericsson’s wireless LAN access point A3. In figure 5.15, the distributions for the Bluetooth headset are shown. When the antenna is placed against the phantom higher measurement values are obtained. The difference in maximum values between the two positions, antenna towards or pointing outwards, is approximately a factor 3.

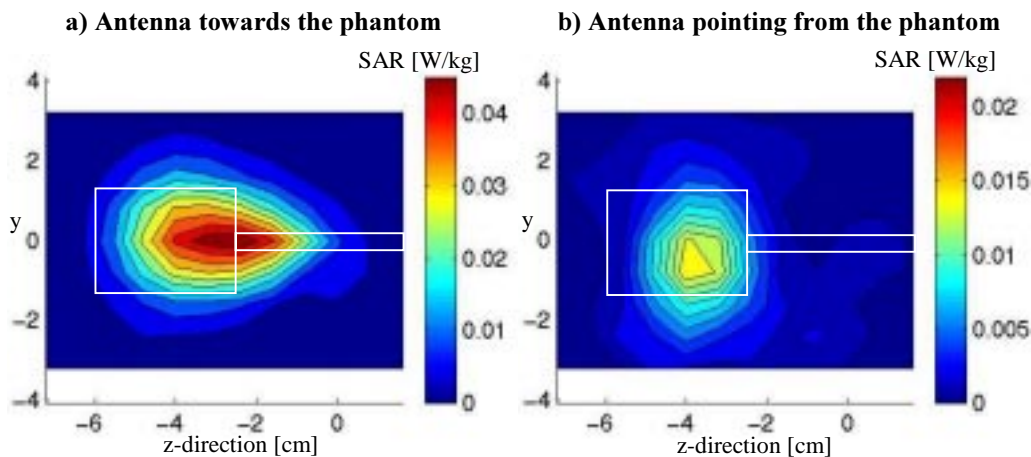


Figure 5.15. SAR distributions measured 6mm from the Bluetooth headset. a) The headset is placed so the antenna touches the phantom. b) The headset has its normal position, with the antenna pointing outwards. The transmitted power was 1mW at a frequency of 2.45GHz.

For the access point a plane 6mm from the edge of the phantom was measured. The plane was the same plane as for the calculations. The distance between the transmitting antenna and the measured plane was 50mm. The antenna was transmitting 50mW with a frequency of 2.43GHz. The SAR distribution is shown in figure 5.16 and the maximum SAR value is well below the basic restrictions.

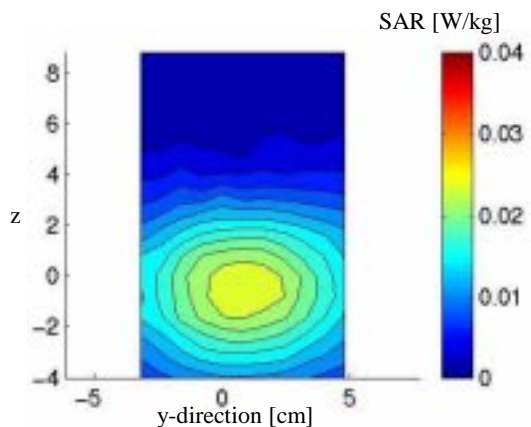


Figure 5.16. SAR distributions measured 50mm from Ericsson’s wireless LAN access point A3 placed 5cm from the phantom, transmitting power 50mW and frequency 2.43GHz.

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5.2.2 Near field distributions

The near fields, 6mm above the Bluetooth headset antenna was well below the reference levels. The measured electric and magnetic fields are shown in figure 5.17. The frequency was 2.45GHz and the transmitted power was 1mW.

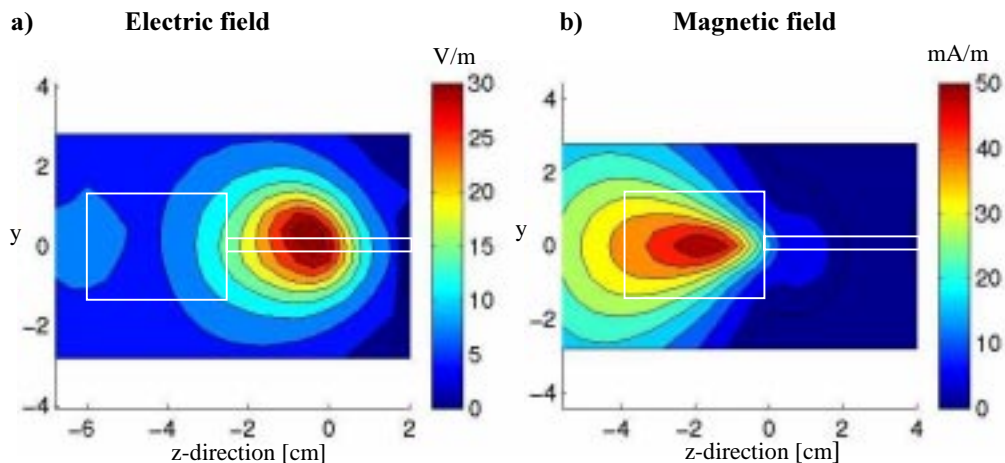


Figure 5.17. Measured fields electric (a) and magnetic (b) field strengths from the Bluetooth headset. The plane measured was situated 6mm from the headset. The transmitted power was 1mW at a frequency of 2.45GHz.

The wireless LAN access point measured gave the field distributions shown in figure 5.18. The distance between the measured plane and the transmitting antenna was 50mm. The antenna transmitted 50mW at a frequency of 2.43GHz. Both maximum electric and magnetic fields are well below the reference levels. Another plane measured situated only 6mm above the transmitting antenna still gave values under the reference levels.

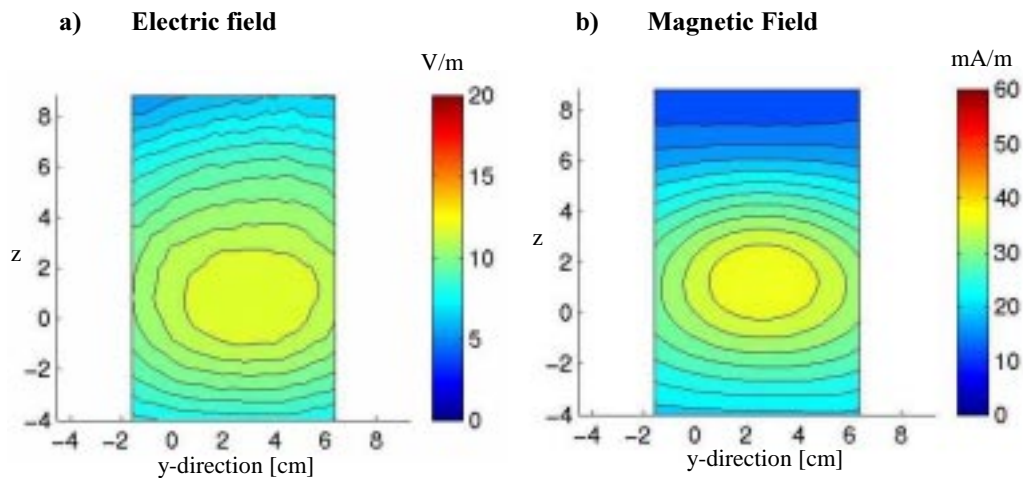


Figure 5.18. Field distributions for Ericsson's wireless LAN access point A3 transmitting 50mW with the frequency 2.43GHz. The distance between the device and the measured plane was 50mm.

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5.3 Discussion

5.3.1 Comparison – calculations vs. measurements

The Bluetooth headset was the one of the two objects to be both calculated in XFDTD and measured with the DASY3 system. There was high agreement between the calculated and the measured data, see figure 5.11a and 5.17a. The disagreement in shape can be due to the simplified model in XFDTD. The box by the ear was made as a rectangle, while in reality the edges were phased.

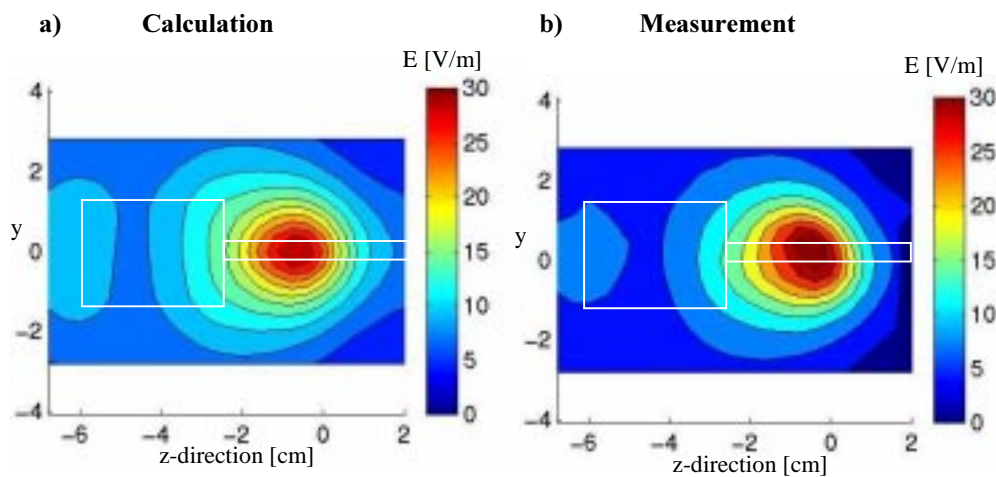


Figure 5.19 (5.11a and 5.17a). A comparison of the calculated electric field from XFDTD (a) and the measured electric field (b) for the Bluetooth headset.

The magnetic field showed a higher disagreement, compare figure 5.11b and figure 5.17b. The squared shape can once again be detected in the XFDTD calculations. The maximum values are in the same range, but the values from XFDTD are about 40 per cent higher.

The differences in the SAR distribution are shown when comparing figure 5.3a and 5.15a. From the worst case scenario, with the headset placed so the antenna was lying against the phantom, both the shape and the magnitude of the SAR distribution have a high agreement between the values calculated and measured.

The other product to be both calculated and measured was Ericsson's wireless LAN access point A3. There was a high agreement in shape for both the field and the SAR distributions, but the values for the measurements very approximately 30 to 40% lower than the calculated values. Figures to be compared are for the electric and magnetic fields 5.14a, b and 5.18a,b and for the SAR distribution figures 5.7 and 5.16. Several possible explanations can be listed why the measured magnitudes were lower for the measurements, see 'Sources of errors'.

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5.3.2 Sources of errors

The sources of errors can be due to many different things. The errors from the calculations have to do with the method, the software or the modeling. From the measurements the errors can be either the measurement system itself or uncertainty parameter during the measurements.

The calculation errors due to modeling naturally include the actual simplifications made in the models in XFDTD. The simplified models were not just made both to adjust the products to the grid step but also simplified to reduce the time when making the models. As shown before, see figure 4.5, the headset was in the reality not formed as three boxes put together but had a more complex design. The wireless LAN access point was also simplified. The modeling uncertainty is expected to be up to 50%. Then the method FDTD itself has an uncertainty of a few per cent. Another error source is the influence from the boundary reflections, which can be detected in figure 5.13.

Errors due to the measurement system are hard to specify [17] but are estimated to be less than 20%.

The differences in the results from the calculations and the measurements are also due to some known, but uncertain factors. The SAR-liquid in the measurements did not have the same properties as the calculated tissue. The conductivity was too high and the relative permittivity was too low in the measurements. Another factor is the uncertainty of the position of the measured device. Furthermore, it was only the nominal value of the output power 1mW and 50mW from the transmitting antenna that was known, the real transmitted powers were not measurable. Other uncertain factors are the antenna efficiency and how the phantom affected the antenna. Finally, the resolution of the SAR assessments was different in the calculations and the measurements. In XFDTD the peak values are calculated over a volume, a voxel where each side is 2mm. The probe measuring SAR in the DASY3 system has an extension of 5mm, which means that the peak values are calculated over a cubical sensor volume of 5×5×5mm. Since the peak value is very local the values calculated over a bigger volume are lower than the values calculated over a small volume.

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6 Summary and conclusions

In this thesis work the exposure from Bluetooth and wireless LAN devices have been studied. Calculations have been made using the Finite Difference Time Domain (FDTD) method and measurements were made on one Bluetooth headset prototype and one wireless LAN access point.

The Specific Absorption Rate (SAR) distribution and the localized SAR averaged over 1g and 10g were the main parameters to be studied. Furthermore, the electric and magnetic field have been calculated and measured. The obtained results have been compared with the basic restrictions and reference levels.

SAR and the field distribution were calculated for a couple of possible Bluetooth products and wireless LAN scenarios. Bluetooth is using the 2.45GHz frequency band, while wireless LAN products either use that band or the 5GHz frequency band. The Bluetooth calculations were divided in two parts, one studying devices transmitting 1mW and the other for devices transmitting 30mW and 100mW. There were three main wireless LAN models in this thesis. The first was wireless LAN products already on the market with a frequency of 2.45GHz, the second used the frequency 5.35GHz and the third 5.725GHz. The output power was 50mW, 200mW and 1W for the three types of models respectively.

This thesis work can be summarized in the following results:

- Bluetooth products transmitting a power of 1mW at a frequency of 2.45GHz can never exceed the basic restriction, no matter how close the antenna is to the person.
- Bluetooth products transmitting 30mW gave SAR values well below the basic restrictions at a distance of 0cm.
- Bluetooth products transmitting 100mW give SAR values well below, about 20 times, the basic restrictions at a distance of 5cm.
- Wireless LAN products transmitting a nominal power of maximum 50mW at a frequency of 2.45GHz have SAR values well below the basic restriction at a distance of 5cm.
- Wireless LAN transmitting a power of maximum 200mW at a frequency of 5.35GHz had SAR values more than three times below the basic restriction at a distance of 5cm.
- Wireless LAN, a half wave dipole antenna transmitting 1W at a frequency of 5.725GHz gave SAR values below the basic restrictions when the distance was 7.5cm. By reducing the output power to 0.7W the basic restriction was reached at 5cm.

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Additional Information

<http://www.bluetooth.com>
<http://www.ericsson.se/wlan>
<http://www.remcom.com>

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APPENDIX

A.1 An analysis of FDTD grid step influence upon 1g and 10g SAR

The purpose with this test was to compare the 1g and 10g SAR from three different grid step sizes, 1mm, 2mm and 3mm at the frequency 2.45GHz. To perform this test three calculations were made in XFDTD, one on each grid step size. A cubic lossy box of brain tissue and a half wave (60mm) dipole antenna was used, placed as in figure A1. The side of the box and the length of the dipole antenna were both 60mm. The distance between the box and the antenna was 6mm. The parameters used for the brain tissue were permittivity 42.5, conductivity 1.5S/m and density 1030 kg/m³.

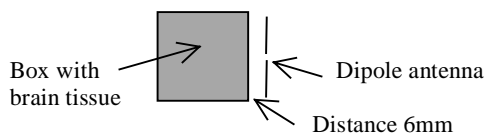


Figure A1. Square box filled with brain tissue and a dipole antenna. The distance is 6mm.

The results, shown in figure A2, show that the average SAR value calculated over 1g increases with the grid step and that the average SAR value calculated over 10g is about the same. The maximum SAR values are very similar, see figure A2c. The quotient of the input power and the radiated power, the efficiency, is affected by the grid step size, see figure A2d. Obviously the maximum efficiency is obtained for the smallest grid step 1mm. In this case the efficiency decreased approximately two percentage, when the grid step size was increased 1mm.

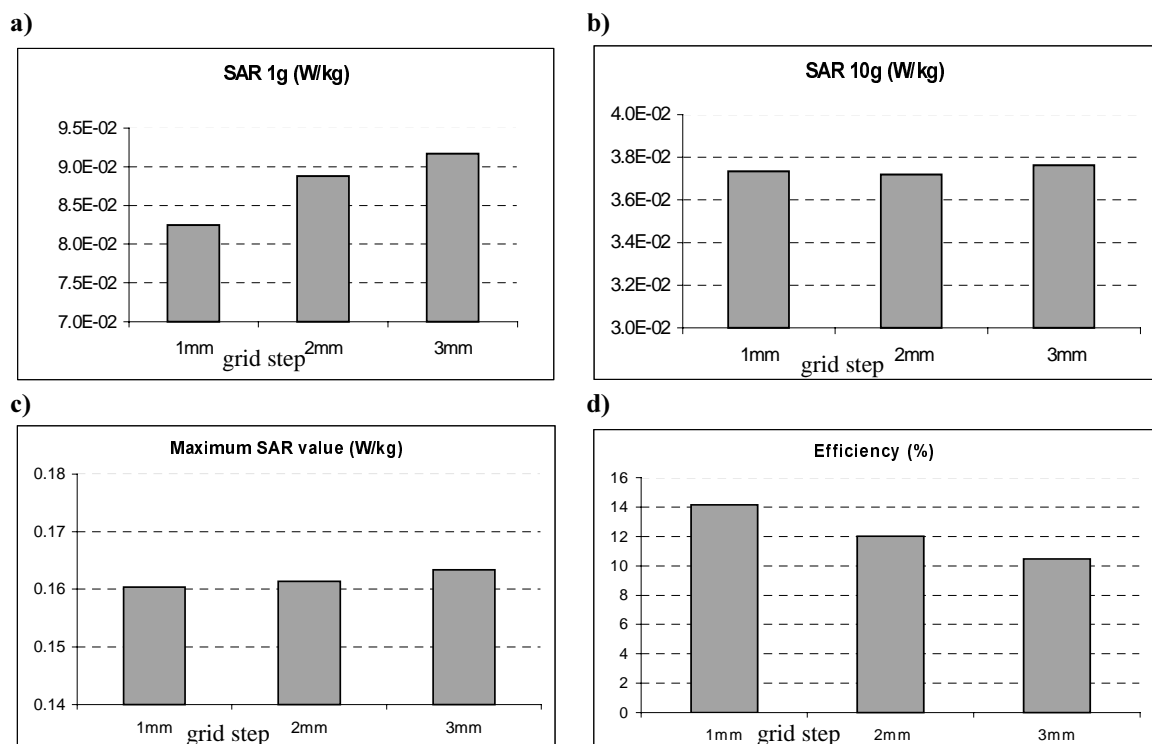


Figure A2. A comparison of three different grid-step sizes, 1, 2 and 3mm. Calculations made on a square box with brain tissue dielectric properties and a dipole antenna. Average SAR value calculated over 1g (a) and 10g (b) of tissue. c) The maximum SAR-value in the three different grid-sizes. d) The antenna efficiency for the three grid-sizes, shown in per cent.

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A.2 SAR-liquid - Experiment results

Some experiments were made trying to find a recipe for SAR-liquid for brain tissue with the frequency 2.45GHz. The ingredients were glycol, Diethylene Glycol Butyl Ether, water and salt. Initially, a recipe for a glycol mixture of SAR-liquid for brain tissue for the frequency 1900MHz was used, see table A.1.

Tissue	Frequency [MHz]	Water [%]	Salt [%]	Glycol [%]	Permittivity [Vs/Am]	Conductivity [S/m]
Brain	1900	54.90	0.18	44.92	39.9	1.42

Table A1: Recipe containing glycol for 1900MHz SAR-liquid and the electrical parameters given.

The equipment used to find the electrical parameters were a network analyzer, a probe and a computer, see figure A.3. The values were taken for the frequency 2.45GHz.

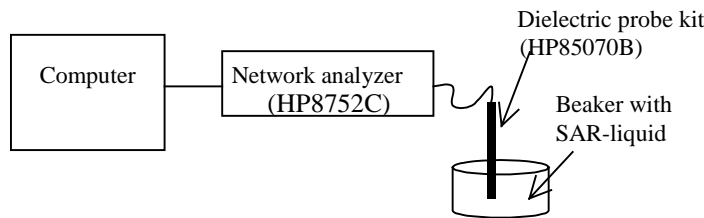


Figure A3. The laboratory setup for measuring the electrical parameters of SAR liquid.

Values for the relative permittivity (ϵ_r or ϵ'), which is the real part of the complex permittivity and the imaginary part of the permittivity (ϵ'') was given by the software. The conductivity was calculated from the imaginary part of the permittivity using the formula $\sigma = 2\pi f \epsilon_0 \epsilon''$. For each mixture tested five measurements were taken on the same SAR-liquid. An averaged value for the real respective imaginary part was calculated for each mixture, before calculating the conductivity.

The values nominal for the tissue simulating liquid were 42.5 for the permittivity and 1.5 S/m for the conductivity. The results, shown in table A.1, show that these experiments did not give such good results. The permittivity was too low in all test results and the conductivity was too high. Adding more water would increase the permittivity, but it would also increase the conductivity, which already is too high. The effect from the salt is increasing the conductivity, which is not desirable. The decision, after these test results, was to use 55% of water and 45% of glycol.

Water [%]	Glycol [%]	Salt [%]	Permittivity [$\Delta\epsilon_r$ [%]	Conductivity [S/m]	$\Delta\sigma$ [%]
55.0	45.0	0.0	39.5	-7.6	1.9	21.0
50.0	50.0	0.0	34.9	-21.8	1.88	20.2
45.0	55.0	0.0	30.7	-38.4	1.79	16.2
54.9	44.9	0.2	38.95	-9.1	2.04	26.5

Table A2. Test results from measuring different mixes trying to receive a useful SAR-liquid.